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VOLUME XVII NUMBER 1

THE
ASTROPHYSICAL JOURNAL

An International Review of Spectroscopy and Astronomical Physics

EDITED BY
GEORGE E. HALE AND EDWIN B. FROST
of the Yerkes Observatory

JANUARY 1903

CONTENTS

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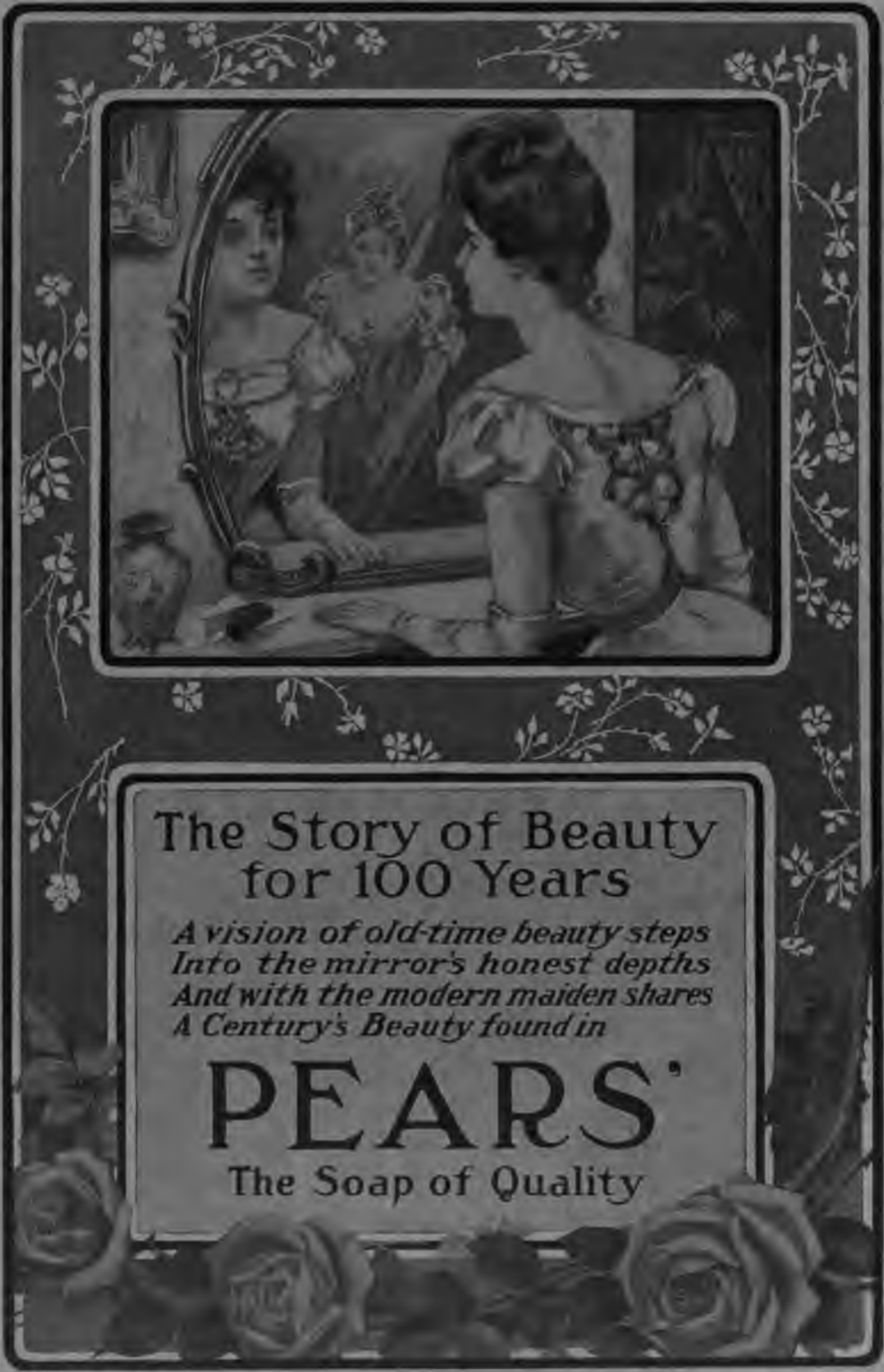

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CONTENTS

NUMBER I.

NUMBER II.

NUMBER III.

NUMBER IV.

NUMBER V.

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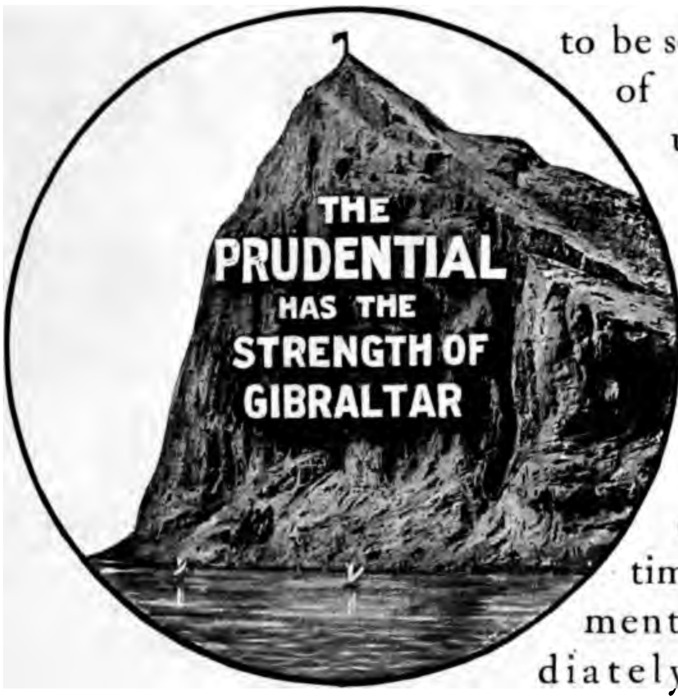
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THE
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VOLUME XVII JANUARY 1903 NUMBER 1

ON THE OPTICAL CONDITIONS REQUIRED TO SECURE MAXIMUM ACCURACY OF MEASUREMENT IN THE USE OF THE TELESCOPE AND SPECTROSCOPE.

By F. L. O. WADSWORTH.

(*Continued from p. 299, Vol. 16, December 1902.*)

B. Causes of asymmetry in the image of Class B may be subdivided as follows:

B (1). Lack of resolving power due to (*a*) small aperture, (*b*) imperfect definition, or (*c*) imperfect achromatism.

B (2). Errors of adjustment of focus.

B (3). Errors due to an asymmetrical arrangement or use of the instrument itself.

B (4). Errors due to erroneous or imperfect design.

B (1). A frequent cause of error in the measurement of the position of a point or line source is an unsymmetrical broadening of the image by the superposition upon it of another image of a second fainter source too close to the former to be clearly "resolved."

If the two sources vibrate independently and have intensities

i_1, i_2, the distribution in intensity in the superposed images is represented by

$$i_1 \frac{\sin^2 \xi}{\xi^2} + i_2 \frac{\sin^2 (\xi - \kappa)}{(\xi - \kappa)^2} , \tag{54}$$

κ being the angular interval between the centers of the two sources, and ξ, the angular distance of any point in the image from the center of the geometrical image of the principal source S_1. An example of the image of such a double source is shown in Fig. 9. The dotted lines represent the separate diffraction images of the two sources, the full line the resulting focal image of the two together.

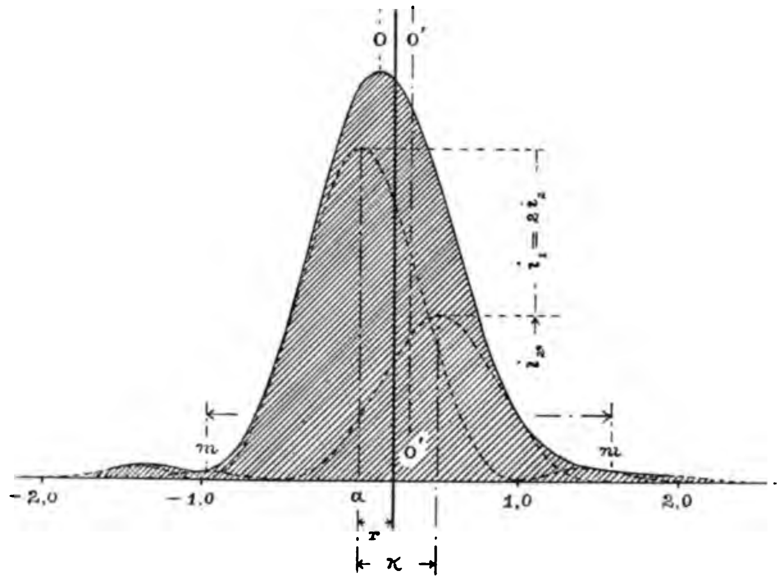

FIG. 9.

In measuring the position of such an image the reference cross-wires are always set too far to the right in the figure, *i. e.*, toward the smaller component, by an amount depending on its intensity in comparison with that of the principal source. Examples of errors of measurement of this kind are found in the determinations of position, proper motion, and parallax of very close double stars.[1] Similar errors in the determination of wave-

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[1] Certain interesting cases of this kind which seem to have escaped attention will be considered fully in a subsequent paper. (Note added January 1903.) One of

lengths of spectral lines have been frequently noted.[1] The only way in which such errors can be detected and corrected is by the use of higher resolving power, by which the two components may be separated and measured separately. It appears probable from the work of Michelson[2] and the more recent work of Perot and Fabry,[3] that by the use of sufficiently high resolving powers a large number of the lines which are now regarded as single will be resolved into two or more components, in many cases of very unequal intensity.

In this case the error of setting the cross-wires is a real one, for the reason that we desire to determine in our measurements the position of one of the components of the double source (generally the brighter one) and not the mean position of the two. If we know the separation of the two sources and their relative magnitude, we may indeed correct the results of the measurements of the double source so as to give with a fair degree of approximation the true position of either component. In general the setting of the cross-wire on such an asymmetrical image as is here being considered will be a compromise between the tendency to set on the point of maximum intensity O, Fig. 9, of the compound diffraction image and the point O', midway between those points of equal intensity mm, which are just perceptible to the eye of the observer. In the case represented in Fig. 9, in which $\kappa = \frac{1}{2} a_0$ and $i_1 = 2 i_2$, the setting of the cross-wire would be about $r = a + 0.4 \kappa$.

---

these cases was recently investigated by Comstock, whose paper, "The Motion of 85 *Pegasi*," was read on December 30, 1902, at the recent meeting of the Astronomical and Astrophysical Society in Washington.

[1] For example, see Rowland's "Table of Standard Wave-Lengths;" KAYSER and RUNGE, "Ueber die Spectren der Elemente," *Abh. d. K. Akad. d. W.*, Berlin, 1888–1892; HASSELBERG, "Untersuchungen u. d. Spectra der Metalle," *Köngl. Svenska Vet. Akad. Handlingar*, 1894–1898; KAYSER, "Influence of Slit-Width on Comet Spectra," *A. N.*, **3217**; *A. and A.-P.*, **13**, 367; HARTMANN, "Wave-Length of the Nebular Lines," ASTROPHYSICAL JOURNAL, **15**, 292; WRIGHT, *ibid.*, **16**, 57, etc.

[2] "Application of Interference Methods to Spectroscopic Measurements," *Phil. Mag.*, (5) **34**, 280.

[3] *Bull. Astron.*, **16**, 5; ASTROPHYSICAL JOURNAL, **9**, 87; *Jour. Phys.*, (3) 9, 369; ASTROPHYSICAL JOURNAL, **15**, 73, etc.

The corrected reading for S_1 is, therefore,

$$a = r - 0.4\kappa\ , \tag{55}$$

and for S_2 similarly

$$a + \kappa = r + 0.6\kappa\ . \tag{56}$$

B (2). Displacements due to imperfect adjustments for focus.

In considering errors of measurement due to this cause alone we shall at first assume optical conditions to be such that the wave-front which forms the image is symmetrical and concentric about the optical axis on which the image is formed; *i. e.*, that there is no unsymmetrical aberration, either spherical or chromatic, and no eccentricity.

When these conditions are fulfilled a change of focus should result simply in a symmetrical expansion of the diffraction disk or band, which represents the physical image of a point or line.[1] The center of each image will remain fixed on the secondary optical axis joining the center of the geometrical image with the optical center of the lens system. Under such conditions the separation of any two such images at the focal distance z from the optical center of the objective is

$$\xi = 2\,z \sin\frac{\kappa}{2}\ , \tag{57}$$

where κ, as before, is the angular separation of the two images. Whence for any change in z

$$d\xi = 2 \sin\frac{\kappa}{2}\,dz = \kappa dz = dz\frac{\xi}{z}\ . \tag{58}$$

This expression is entirely independent of f, the true focal length of the instrument, and hence if z could always be maintained *constant*, dz and, therefore, $d\xi$, would be zero, no matter what the *absolute* value of z might be. This is only possible under absolutely constant temperature conditions. When the temperature changes, z will also change, first, on account of the thermal expansion or contraction of the telescope tube, and, second, on account of the mechanical refocusing which may be necessary in order to compensate for the corresponding tempera-

---

[1] This is a common way of testing the excellence either of an objective or of atmospheric conditions.

ture change in f. We can best consider these two effects separately.

1. The change in z, due to the thermal change in the length of the telescope tube, for a difference of temperature Δt will be

$$\begin{aligned}\frac{\delta}{dt} z &= a z \Delta t \\ &= \frac{d\xi}{2 \sin \frac{\kappa}{2}} ,\end{aligned}$$

where a is the coefficient of expansion of the material of which the telescope tube is made. But we have also a similar change in the scale of the measuring or recording device at the focal plane, which amounts to

$$- d\xi' = - a' \left(2z \sin \frac{\kappa}{2} \right) \Delta t .$$

The apparent change in the separation of the two images as indicated by the reading of the instrument is therefore

$$d\xi + (- d\xi') = 2z \sin \frac{\kappa}{2} (a - a') \Delta t = \Delta_m \xi . \qquad (59)$$

If the material of the micrometer screw or reference scale is the same as that of which the telescope tube is constructed, then $a' = a$ and $\Delta_m \xi = 0$; *i. e.*, in this case the measured separation of the images at the focal distance, z, remains the same at all temperatures.

If the position of the images is first recorded photographically on a sensitive plate, and afterward measured by a comparator or similar device, we have to consider not only the relative expansions of the glass plate and the telescope tube, but also those of the plate and the scale or screw of the comparator. In this case the total change in the measured distance as indicated by the reading of the comparator at a temperature $T = t_0 + \Delta' t$ is

$$\sum_{t}^{T} d\xi = 2z \sin \frac{\kappa}{2} \{ (a - a') \Delta t + (a' - a'') \Delta' t \} . \qquad (60)$$

In order to make (60) vanish we must have

$$(a - a') \Delta t = (a'' - a') \Delta' t .$$

This condition may be satisfied in one of three ways: (*a*) by making $a'' = a$ and $\Delta' t = \Delta t$; *i. e.*, by making the screw or scale of the comparator of the same material as the telescope tube and measuring the plate at the same temperature at which it was photographed. This plan is generally neither convenient nor practicable; (*b*) by controlling the temperature, T, of measurement, so that for given values of a, a' and a'' we always fulfill the relation

$$T - t_0 = \frac{a - a'}{a' - a''} = (t - t_0) \ .$$

This is also inconvenient and troublesome, although less so than the preceding; (*c*) by making $a = a' = a''$; *i. e.*, by constructing both the telescope tube and the comparator scale of glass or platinum. This, while impracticable for large telescopes, is not at all so for small ones, such as are used for spectroscopes.

Instead of attempting to make the correction (60) vanish we may simply determine its amount and apply it to the measurements. In this case we need to determine the degree of accuracy with which the temperatures t_0, t, and T must be known. This is easily done by equating the differential of (60) with the limiting value of ϵ expressed in linear measure, *i. e.*,

$$\epsilon_0 = \epsilon f \cong \epsilon z \ .$$

This gives at once from (60) and (14)

$$\frac{\delta}{dt} \{ (a - a') \Delta T + (a' - a'') \Delta' t \} \, dt = \frac{\lambda}{15 b \kappa} \ . \tag{61}$$

The values of a, a', and a'' for brass, glass, and steel (the materials usually employed) are respectively

$$a \cong 0.000018 \qquad a' = 0.000008 \qquad a'' = 0.000010.$$

In case of the Mills spectrograph the aperture b is about 3.7cm. Hence for an angle $\kappa = 1^\circ\!.5 = 0.027$[1] we have for (61),

$$dt = \frac{40}{10 \frac{\delta}{dt} \Delta t - 2 \frac{\delta}{dt} \Delta' t} \ , \tag{62}$$

and if we assume that it is equally easy to measure all three temperatures, t_0, t, and T, (62) indicates that the error (which

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[1] See Table II of this paper.

must be taken without regard to sign), in determining any one of them must not exceed 1°.6. It is generally possible to be certain of all these temperatures to this or even a higher degree of accuracy, and it is therefore usually better to observe them and correct the observed readings of the comparator than it is to attempt to eliminate the corrections by any of the methods indicated in the preceding paragraph.

2. *Effect of refocusing:* In large telescopes the alteration of the true focal length, f, for a given change in temperature is so much greater than the corresponding thermal alteration in z alone, that it is necessary to refocus the eyepiece or plate in order to obtain good definition. Such refocusing is also essential, as will be shown later, even in small instruments, if there is any unsymmetrical aberration or eccentricity in the incident wave-front. In such cases we have

$$\begin{aligned} dz &= \frac{\delta}{dt}(z + d\Omega) + d\Omega \\ &= (z + \delta\Omega)\,a\Delta t + d\Omega \\ &= \frac{d\xi}{2\sin\frac{\kappa}{2}} \end{aligned} \qquad (63)$$

where $d\Omega$ represents the actual mechanical movement of the eyepiece or plate in refocusing. The change in the separation of the two images at the new focal plane, as indicated by the micrometer screw or comparison scale, now is

$$\Delta\xi = 2\,(z + d\Omega)\sin\frac{\kappa}{2}\left\{(a - a')\,\Delta t + \frac{d\Omega}{z + d\Omega}\right\}, \qquad (64)$$

and in the case of comparator readings on photographs

$$\Sigma\xi = 2\,(z + d\Omega)\sin\frac{\kappa}{2}\left\{(a - a')\,\Delta t + \frac{d\Omega}{z + d\Omega} + (a' - a'')\,\Delta' t\right\}. \qquad (65)$$

If we assume that the terms of (64) and (65) which represent temperature corrections are computed as before and applied to the measurements, we have left to consider only the effect of the term

$$2d\Omega \cdot \sin\frac{\kappa}{2} = \kappa d\Omega\ .$$

In order that this may be computed also with the same degree of accuracy as already assumed we must have

$$d(d\Omega) \leqq \frac{\epsilon f}{\kappa} = \frac{\lambda}{30\beta\kappa} \; , \tag{66}$$

β being the semi angular aperture.

The degree of accuracy which it is necessary to observe in refocusing (*i.e.*, in determining the amount of mechanical shift of the eyepiece or plate with reference to the telescope tube) is therefore independent of the size of the instrument and depends only on its form (*i.e.*, its angular aperture), and the angular separation of the two objects measured. We will determine what this is in a few cases of particular interest.

For large visual telescopes and heliometers, $\beta \cong 0.027$. Hence for $\kappa = 0^\circ\!.35 = 0.0061$,[1] and $\lambda = 0.000056$ cm.,

$$d(d\Omega) \leqq 0.01 \text{ cm} \cong \frac{1}{250} \text{ in.} \tag{67}$$

For photographic telescopes and concave gratings of sufficiently long focus to give full photographic resolution $\beta \cong 1/80 \cong 0.013$. The field κ is, however, correspondingly larger. For Rowland's concave gratings, for example, $\kappa \cong 0.074$ (more than 4°). For such cases therefore

$$d(d\Omega) \leqq 0.002 \text{ cm} \; , \tag{68}$$

or less than one one-thousandth of an inch.

From the above results, (66), (67), and (68), it would appear necessary that the focusing scales of large telescopes designed for micrometric or heliometric work should be provided with verniers capable of reading to 0.1 mm, while those for the view telescopes of large spectrographs and spectrometers should be capable of reading to at least $1/50$ mm.

The accuracy of focusing demanded in all these cases is considerably higher than is usually considered necessary, or is attained. It is, of course, far in excess of either visual or photographic requirements on the standard of either resolution or general optical definition. But as we have already stated, this

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[1] This is the limit imposed by considerations of aberrational distortion in the case of the Lick and Yerkes telescopes (see Table II). This limit has, however, been exceeded in a number of cases of individual measures with these instruments.

standard is an inadequate and unsafe one to apply as a test of the *accuracy* of an optical instrument.

In the case of a telescope used as a collimator the accuracy of focusing necessary depends on the nature and method of use of the instrument.

In general, any lack of exact collimation may be compensated by altering the focus of the observing telescope, and if the change in the latter is not objectionable and everything remains symmetrical with respect to the axis of collimation, no error can be thus introduced. In the case of prism spectroscopes, however, the condition of symmetry with respect to the x axis cannot be fulfilled, and any divergency or convergency in the beam of light coming from the collimator objective will result in the introduction of an unsymmetrical aberration in the wave-front traversing the prism train, the amount of which will depend on the curvature of the incident wave front, the optical perfection of the prisms themselves, and the angles of incidence on the successive faces of the prisms.

The simplest case to consider is that in which the axis of the incident wave-front traverses the train at minimum deviation, the faces of the prisms are optically plane, and the material of which they are composed is of uniform optical density. The amount of longitudinal aberration produced by the passage of a cone of light of semi-angular aperture θ through a single prism under the conditions assumed above has been calculated by Rayleigh, who finds[1]

$$\delta v = 3\theta u \frac{\tan i}{\cos^2 i'} \cdot \frac{(n^2 - 1)}{n^2}, \tag{69}$$

where i and i' are the angles of incidence on the first and second faces of the prism and u is the radius of the spherical wave-front.

We have also the relation[2]

$$\delta v = \frac{3E}{\beta^2}, \tag{70}$$

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[1] Rayleigh, *Phil. Mag.*, (3) 9, 40–49. See also "Theory of the Ocular Spectroscope," Astrophysical Journal, 16, 2, July 1902.

[2] Rayleigh, *Phil. Mag.*, (3) 8, 411. The result there given is for a symmetrical aberration depending on x^4. For an unsymmetrical aberration depending on x^3 the numerical factor in the numerator is 3, not 4.

where β is the semi-angular aperture of the cone of rays emerging at the second face of the prism. Hence if we denote the aperture of the collimator by b and the length of path of the central ray through the prism by L, we have

$$\theta_1 = \frac{b}{2v} \cong \frac{b}{2(u+nL)} \cong \theta\left(\frac{u}{u+nL}\right) . \tag{71}$$

Also

$$\frac{1}{f} - \frac{1}{f+df} = -\frac{1}{u} . \tag{72}$$

whence

$$u = -\frac{f(f+df)}{df} , \tag{73}$$

and

$$\theta_1 = -\frac{bdf}{2\{f^2 + (f-nL)df\}} . \tag{74}$$

In most cases the quantity $(f-nL)$, which represents the difference between the principal focal length of the collimator and the optical path of the central ray through the prism, is so small that the second term of the denominator in (74) is vanishingly small compared to f^2 and may be neglected.

We then obtain at once from (69), (70), (71), and (74)

$$E = \beta^3 \frac{(df)^2}{f} \cdot \frac{\tan i}{\cos^2 i'} \cdot \frac{(n^2-1)}{n^2} , \tag{75}$$

where β as before denotes the semi-angular aperture of the collimator objective.

The limiting value of df will be found by equating (75) and (14), which gives

$$df = \pm \frac{n \cos i'}{4\beta} \sqrt{\frac{f\lambda}{\beta \tan i\,(n^2-1)}} . \tag{76}$$

If we neglect the successive changes of the second order in the value of θ, which are indicated in (71), we have similarly for N prisms

$$E_N = NE ,$$

$$\therefore\ df_N = \frac{df}{\sqrt{N}} . \tag{77}$$

In the case of a spectrometer which has a collimator of focal length $f = 100$cm and aperture $b = 5$ cm, and a prism train consisting of a single 60° prism of light flint of index 1.6 for $\lambda = 0.00005600$, we have $\beta = 0.025$, $i = 53^\circ\ 7'\ 48''$, and $i' = 30^\circ$. For this case then

$$df = \pm 4.55\,\mathrm{cm}\ , \tag{78}$$

which shows that under the conditions assumed above a very considerable range is permissible in focusing the collimators of even very large spectrometers.

This conclusion is so at variance with the commonly accepted statement that an accurate focusing of the collimator is very important[1] that it is liable to be misinterpreted unless carefully considered. It is only true when the minimum deviation condition is strictly fulfilled. It is necessary therefore to consider, first, the degree of accuracy with which the various parts of the spectrometer train may be adjusted and maintained in their correct relative positions, and second, the amount by which a given error in adjustment will affect the results given in (75) and (76).

With any given instrument it is always possible by simple hand adjustment alone to bring the prism to a position of minimum deviation with an error not exceeding that which would produce a displacement of the image equal to ϵ, the metrological power of the view telescope. The relation between the angular displacement θ of the prism from the position of minimum deviation and the resulting change in deviation of the central ray has been determined by the writer, who finds for small values of θ,[2]

$$\left.\begin{aligned} \Delta &= \Delta_0 + \sin^{-1}\theta^2\left(1+\frac{\theta^2}{2}\right)\frac{\sin\dfrac{\phi}{2}(n^2-1)}{n\cos^2\dfrac{\phi}{2}\sqrt{1-n^2\sin^2\dfrac{\phi}{2}}} \\ \text{or}\quad \delta &= \Delta - \Delta_0 \cong \theta^2\left[\frac{\sin i}{\cos i\cos^2 i'}\cdot\frac{(n^2-1)}{n^2}\right] \cong C\theta^2 \end{aligned}\right\}, \tag{79}$$

where Δ_0 is the angle of minimum deviation of the ray, and Δ

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[1] See for example SCHUSTER, *Enc. Brit.*, article "Spectroscopy;" HARTMANN, ASTROPHYSICAL JOURNAL, **12**, 36; FROST, ASTROPHYSICAL JOURNAL, **15**, 15, etc.

[2] ASTROPHYSICAL JOURNAL, **2**, 280. The expression there given is in error. The term $\sqrt{1-n^2\sin^2\frac{\phi}{2}}$ should appear only in the denominator and not in the numerator.

the deviation when the prism has been displaced from the correct position for Δ_0 by an angle θ. If, therefore, we put $\delta = \epsilon \cong \frac{1}{16}\frac{\lambda}{b}$ we have for θ

$$\theta = \frac{1}{4} n \cos i \sqrt{\frac{\lambda}{b \tan i (n^2 - 1)}} \,, \qquad (80)$$

an expression very similar to (76). For the case of the spectrometer above considered

$$\theta = 0.0008 \cong 3' \,.$$

This is about as accurately as the prism can be maintained at minimum deviation with the ordinary sliding link movement, unless great care is taken in its construction. With such a device therefore it is useless to set the prism with any greater exactness than is indicated above.

If, however, we use a pivoted link minimum deviation device or, better still, a fixed arm prism train,[1] we can control the movement of the prism much more accurately and can then use a more accurate method of initial setting, for example a theodolite, with advantage. We may thus with ease increase both the initial and continuous accuracy of adjustment at least three times, *i. e.*, we can reduce θ to not more than 1′.

It is next necessary to determine the effect of a given value of θ on the aberration as given by (69) or (75).

The expression for the longitudinal aberration produced by the passage of a cone of light through a prism placed in any position with reference to the axis of the ray can be deduced from the general fundamental equations given by Rayleigh in the paper to which reference has already been made. The expressions thus obtained are, however, complicated and cumbersome to reduce, and for small angles of inclination to the position of minimum deviation the total aberration may be obtained in a more simple way in the following manner:

Let *caa′*, *coo″*, Fig. 10, be the central and edge rays passing through the prism. Owing to the difference θ in the angles of incidence, the total deviation of the two rays in passing through the prism will differ from each other by a small angle $o'a'o'' = f(\theta)$

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[1] *Phil. Mag.*, (5) **38**, 337, October 1894.

which we will call D. Since the wave-fronts are by supposition very nearly plane, the extreme edge aberration E between the incident wave-front ao and the refracted wave front $a'o'$ will be

$$E = o'o'' \cong ao \cdot D = u\theta D = u\theta f(\theta) \ . \tag{81}$$

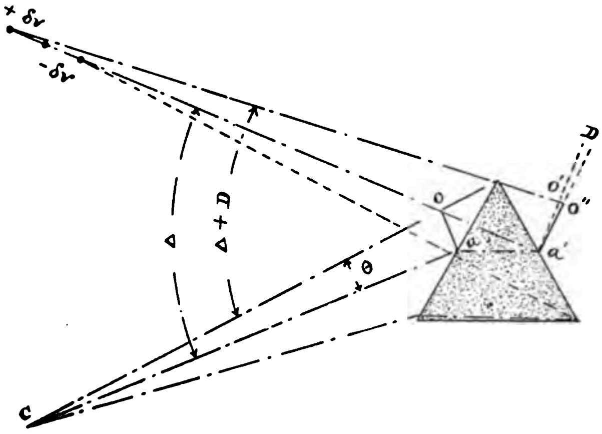

FIG. 10.

When the central ray falls upon the first face of the angle of incidence i for minimum deviation, we have from (79)

$$f(\theta) = \delta = C\theta^2 \ ,$$

and

$$E_0 = Cu\theta^3 = \theta^3 u \frac{\tan i}{\cos^2 i'} \cdot \frac{(n^2 - 1)}{n^2} \ , \tag{82}$$

and from (70)

$$\delta v = 3\theta u \frac{\tan i}{\cos^2 i'} \cdot \frac{(n^2 - 1)}{n^2} \ , \tag{83}$$

the same expression as obtained by Lord Rayleigh.[1]

The method above indicated of determining the aberration of a prism applies not only to the position of minimum deviation but also to any other position within which equation (79) holds. When the central ray is incident on the prism at an angle

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[1] It is perhaps worth while to note that the expression for the longitudinal aberration of a prism deduced by Abbot and Fowle, *Amer. Jour. Sci.*, (4) **2**, 253, and *Annals of the Smithsonian Astrophysical Observatory*, **1**, 78–79, is based upon an erroneous assumption. If equation (12) of their paper were correct there would be no aberration, *i. e.*, the angular deviation of the central and extreme rays would be the same.

other than that for minimum deviation, say at an angle $i \pm \kappa$

$$\begin{aligned}\Delta_c &= \Delta_0 + f(\kappa)\\ &= \Delta_0 + C\kappa^2 .\end{aligned}$$

And for the extreme ray incident at an angle $i \pm (\kappa + \theta)$ we have similarly

$$\Delta_e = \Delta_0 + C(\kappa + \theta)^2 .$$

Hence

$$D = C(2\kappa\theta + \theta^2) , \tag{84}$$

and the wave-front aberration E is

$$E_\kappa = Cu\theta^3\left(1 + \frac{2\kappa}{\theta}\right) , \tag{85}$$

$$= \beta^3 \frac{(df)^2}{f^2} \cdot \frac{\tan i}{\cos^2 i'} \left(\frac{n^2 - 1}{n^2}\right)\left(1 - \frac{4\kappa f^2}{bdf}\right) , \tag{86}$$

As before, we obtain the limiting values of df for a single prism by equating (86) and (14). This gives us after reduction

$$df = \frac{\kappa f}{\beta} \mp \frac{n \cos i}{4\beta} \sqrt{\frac{\lambda f}{\beta \tan i\,(n^2 - 1)} + \frac{16\kappa^2 f^2}{n^2 \cos^2 i'}} , \tag{87}$$

which for large values of κ may be reduced to the form

$$df = \mp \frac{1}{32} \frac{\lambda}{\kappa} \cdot \frac{n^2 \cos^2 i'}{\beta^2 \tan i\,(n^2 - 1)} . \tag{88}$$

When the prism train contains N prisms, each of which is out of the position of minimum deviation by the same amount κ, the total aberration E_N (to the same degree of approximation as before) is N times that for a single prism. If we call the first term under the radical in (87) A and the second term B, we have for N prisms

$$df_N = \frac{\kappa f}{\beta} \mp \frac{n \cos i}{4\beta} \sqrt{\frac{A}{N} + B} . \tag{89}$$

For $\kappa = 0$ we have as before

$$df_N = \frac{df}{\sqrt{N}} , \tag{90}$$

and for large values of κ

$$df_N = \frac{df}{N} , \tag{91}$$

i. e., the effect of adding to the number of prisms in the train is greater as the departure from the position of minimum deviation increases.

The permissible values of *df* both for a single prism and for a train of three prisms have been computed for the spectrometer already considered (in which $f = 100$ cm, $\beta = 0.025$ and $\mu = 1.6$ for $\lambda = 5600$ tenth-meters) for a series of successively increasing values of κ from $\kappa = 1'$ to $\kappa = 10°$. They are given in columns 2 and 3 of Table III.

TABLE III.

κ	df_κ, $N = 1$	df_κ, $N = 3$	K	df_κ, $N = 1$	df_κ, $N = 3$
	cm	cm		cm	cm
0° 0′ 0″	−4.55	2.62	....	....	.....
0° 1′ 0″	−3.54	1.77	....	....	.....
0° 3′ 0″	−2.25	0.90	....	....	.....
0° 15′ 0″	−0.57	0.21	....	....	.....
0° 30′ 0″	−0.26	0.12	0° 30′ 0″	0.57	0.21
1° 0′ 0″	−0.15	0.06	1° 0′ 0″	0.26	0.12
1° 30′ 0″	−0.10	0.035	1° 30′ 0″	....	.....
2° 0′ 0″	−0.07	0.023	2° 0′ 0″	0.15	0.06
2° 15′ 0″	−0.066	0.022	....	....	.....
3° 0′ 0″	−0.049	0.016	3° 0′ 0″	0.10	0.035
....	....	.....	4° 0′ 0″	0.07	0.023
5° 0′ 0″	−0.029	0.010	....	....	.....
10° 0′ 0″	−0.016	0.005	10° 0′ 0″	0.03	0.010

As κ increases, the permissible values of *df* decrease, at first very rapidly and then much more slowly. For large values of κ *df* must be very small; *i. e.*, the focusing must be very exact, especially with several prisms. This is the reason why Schuster's method of focusing (in which the prism is turned far out of the position of minimum deviation, first on one side and then on the other) gives such accurate results. Thus Table III shows that when the displacement κ is 10°, errors of focusing of only 0.016 cm, or of 1 part in 6,000, become manifest with a single prism. It is probably for this reason also that the statement already alluded to on p. 11 has been so often made.

Further consideration of the values of *df* for such values of κ as may be likely to occur because of errors of adjustment, shows, however, that so far as this cause is concerned we still have a very considerable latitude in the adjustment of the collimator. Thus if the error of adjustment κ does not exceed $3'$, as assumed on p. 12, the focusing of the 100 cm collimator need not be closer than 2 cm for one prism or 0.9 cm for three prisms. For $\kappa = 1'$, errors of focusing as large as 3.5 cm and 1.75 cm for one and three prisms respectively may be permitted.

In the case of the spectrograph, in which a considerable angular field is under simultaneous observation, it is of course impossible to adjust the prisms to minimum deviation for all parts of the field at once. If we suppose that the prisms are accurately adjusted to minimum deviation for the central image in the field (wave-length λ_0) and that the maximum semi-angular field, corresponding to spectral images of wave-lengths λ and λ', is K, the amount κ by which a single prism is out of minimum deviation for these wave-lengths is

$$\begin{aligned} \frac{1}{2}(K \pm \delta) &= \frac{1}{2}\{K \pm c(\kappa^2)\} \\ \text{and} \quad \kappa &\cong \frac{1}{2}K . \end{aligned} \tag{92}$$

The required accuracy of focusing is obtained as before from (87). Values of df for $K = 30'$, 1°, 2°, 3°, 4° and 10° ($\kappa = 15'$ to 5°) are given in Table III, column 5.

When the prism train consists of N prisms and the maximum semi-angular field is K_N as before, the amount by which each prism of the train is out of minimum deviation is:

$$\begin{aligned} &\text{for the first prism,} && \kappa_1 \cong \frac{1}{2N} K_N ; \\ &\text{for the second prism,} && \kappa_2 = \frac{3}{2N} K_N ; \\ &\text{for the third prism,} && \kappa_3 = \frac{5}{2N} K_N ; \\ \text{and} \quad &\text{for the } N\text{th prism,} && \kappa_N = \frac{2N-1}{2N} K_N . \end{aligned}$$

The total aberration, E_N, in the train is, under such circumstances [see (85)],

$$\begin{aligned} E_N &= Cu\theta^3 \sum_{\kappa_1}^{\kappa_N} \left(1 + \frac{2\kappa}{\theta}\right) , \\ &\cong C\beta^3 \frac{df^2}{f} \left\{ 1 - \frac{4f^2}{bdf} \cdot \frac{K_N}{2} \right\} N , \end{aligned} \tag{93}$$

and the permissible errors *df* for the train are therefore the same as for a train of N prisms each of which has an error of adjustment κ equal to

$$\frac{K_N}{2}.$$

The value of *df* for this case for three prisms and for the same semi-angular fields as before are given in the last column of Table III.

It will be seen that even for semi-angular fields as large as 2° (total 4°) the permissible range in focus of a 1 meter collimator is nearly ¼ mm, a comparatively large quantity compared to that which expresses the permissible range in focus of the view telescope. The statement already made that the accuracy required in focusing the collimator is much less than that required in focusing the view telescope is therefore generally true, not only for single prism spectrometers, but for large multiple prism spectrographs with fields of 3° or 4°.

In this latter case, however, the range of focus is not sufficiently great to permit us to collimate over more than a limited range of wave-lengths or to disregard altogether changes in temperature in the apparatus. In a well-designed objective of the usual two-lens type, of the size and angular aperture assumed above, the change in focus, df_λ, is between $0.0004f$ and $0.0005f$ for a change of wave-length of 600 tenth-meters on each side of the minimum focus. For the three-prism spectrograph having a field of 4° (total) the permissible range of focus, as stated above, is about ¼ mm or $0.00023f$ on each side of the point of exact collimation. By setting the slit at a point about this distance outside the minimum focus we can therefore collimate the rays with the required degree of accuracy over a maximum total range of nearly 1,200 tenth-meters.[1] In this case, in order to *maintain* the accuracy of collimation over the entire range we must refocus the collimator for every change in temperature. On the other hand, if we set the slit at the exact focus of the collimator for any given wave-length and given

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[1] This is a little less than the results claimed by Hartmann with the Potsdam three prism spectrograph. ASTROPHYSICAL JOURNAL, **12**, 39.

temperature, t, the required accuracy of collimation will be maintained for that particular spectral region over a range of temperature Δt such that

$$\Delta t = \left[\frac{\delta}{dt}(z) - \frac{\delta}{dt}(f)\right] = 0.00023f \ ;$$

or, since $\frac{\delta}{dt}(z) = az$ and similarly $\frac{\delta}{dt}(f) = a'''f$,

$$\Delta t \cong \frac{0.00023}{a - a'''} \ . \tag{94}$$

For objectives of the usual crown and flint glass the second term of the denominator a''' is about 0.000025 for 1° C. For brass and steel the values of a are about 0.000018 and 0.000010, as already given. Hence we have for $\Delta t_{\max}$:

$\Delta t_{\max} \cong 15°$ C. for steel a tube

$\Delta t_{\max} \cong 30°$ C. for a brass tube.

In general the most satisfactory procedure is to limit the range of wave-lengths for which we attempt to secure simultaneous collimation so as to leave a certain range of focus for changes in temperature. If we content ourselves with collimation over a range of 600 tenth-meters (which in the case of most three-prism spectroscopes represents an angular field of about four degrees) we have left to take care of temperature changes a range of focus of about $0.00012f$, which permits a maximum temperature variation

$\Delta t_{\max} \cong 7.5°$ for a steel tube
$\Delta T_{\max} \cong 15°$ for a brass tube

without refocusing.

It is very evident from (94) as well as from our previous considerations with reference to the focusing of the view telescope that so far as avoiding the effect of temperature changes is concerned, brass is a much more satisfactory material than steel to use for telescope tubes. Indeed it is possible by using this metal in conjunction with suitable varieties of glass to obtain almost perfect equality between the temperature coefficient of expansion a' and the corresponding temperature coefficient of focal length a''' so that the range Δt of (94) may be increased and the quantity $d\,\Omega$ of (63) reduced to zero. Two troublesome adjustments and errors are thus avoided. The more detailed results of this investigation will be given in a subsequent paper.

[*To be concluded.*]

RESEARCHES ON THE ARC-SPECTRA OF THE METALS.

VI. SPECTRUM OF MOLYBDENUM.

By B. HASSELBERG.

(*Concluded from p. 319, Vol. 16, December 1902.*)

RESULTS OF OBSERVATIONS.

AFTER thoroughly taking into account the above comparisons I have collected in the following catalogue the wave-lengths of those lines of the arc-spectrum molybdenum which must be ascribed to this metal as far as may be judged at present. It will not be suprising if there should be among them doubtless a few and perhaps many which further investigation will show to be foreign lines, in view of the richness of the spectrum; nor if the use of stronger currents should make it possible to increase considerably the number of lines characteristic of the metal. The corrections and additions resulting under such circumstances can, however, refer only to the faintest lines, and it may therefore be hoped that this catalogue represents all of importance in respect to the spectrum of the metal.

In regard to the arrangement of the catalogue nothing needs to be added to what I have said in my previous papers. It may only be recalled that as before the wave-lengths given are the means of the results of two wholly independent series of measures, made on different plates, the internal agreement of which may be designated as satisfactory in every respect. The deviations of the values of the two series from each other are as follows:

	Tenth-Meters		Tenth-Meters
In 330 cases - - - -	0.00	In 10 cases - - - -	0.06
In 462 cases - - -	0.01	In 2 cases - - -	0.07
In 236 cases - - - -	0.02	In 3 cases - - - -	0.08
In 93 cases - - -	0.03	In 3 cases - - -	0.09
In 45 cases - - - -	0.04	In 1 case - - - -	0.10
In 16 cases - - -	0.05		

Hence the cases in which this deviation exceed the value of 0.02 constitute only about 14 per cent. of the whole. The probable error of a wave-length therefore would in general not reach the amount of 0.02, an estimate which is shown to be practically correct by other circumstances as will be shown below.

Mo λ	R.	*i*		Remarks
		Mo	⊙	
3463.78				
65.81		1.2		
66.98		2		
67.13		1.2		
68.02		2−		
68.70		1+		
69.39		2		
69.80		1		
71.09		1.2		
.....	3473.43			
75.19		2		
76.15		2−		76.07 *Cu*
79.60		2		
80.26		1.2		
81.95		1.2		
82.55		2		
84.05		2		
90.42		1		
.....	3491.46			
91.92		1		
92.05		1+		
92.98		1		
93.49		2−		
3498.21		1+		
3504.55		2.3	2	Also *Fe* 04.56; *V* 3504.57
05.45		2+		
07.16		1		
07.45		1		
08.26		2.3		
10.93		1.2		
.....	3512.78			
13.86		1.2		
14.93		1+		
17.70		2		
18.35		2		
21.17		1.2		
			1	
21.32		1.2		
21.56		2.3		
22.52		1.2		
24.76		2+		
25.11		2+		
26.08		1+	?	
3531.44		1+		
.....	3532.72			
3534.83		1.2		Very diffuse. *Mo?*
37.41		3		
39.07		1.2		
39.62		1		
42.32		2.3		
42.92		1		
43.27		1+	?	
47.57		1+		
48.05		1+		
48.88		1		
51.12		1.2		
52.57		1	2	*Mo ?*
.....	3553.62			
54.35		2−		
55.58		1.2	2	Coinc. *Mo?*
57.63		1		
58.25		3		At edge of ⊙ line 58.21
59.42		1		
60.28		2		At edge of ⊙ line 60.28
62.26		2−	1	
63.30		2.3	1	
63.91		2−		
64.45		1.2		
66.20		2+	?	
66.57		1		
66.91		1		
70.63		1.2		
70.82		2.3		
71.42		1.2		
.....	3573.54			
74.05		2.3	2.3	⊙ has 74.05? 73.97 *Fe*
74.63		1.2		
75.78		1.2		
75.88		1.2		
76.35		1.2		
80.70		2	?	
81.15		1		
82.03		3.4		
83.30		4+		
3584.42		1.2		

Mo λ	R.	*i* *Mo*	*i* ⊙	Remarks
3585.74		1+		
87.02		2 −		
89.10		2		At edge of ⊙ line 89.05
90.47		1		
90.90		2+		
91.55		1.2		
94.73		1		
.....	3595.45			
95.71		2−		
95.87		2−		
96.54		1−		
3599.05		2		
3600.04		1.2		
03.10		2.3		
03.86		1.2		Between the ⊙ lines 03.92 *Ti* .83 *Cr*
04.24		2−		
04.73		1.2		
05.19		1+	?	
07.56		1		
08.52		2+		
10.80		1−		
12.15		2−		
12.62		2−		
13.55		2−		
13.80		1.2		} Overlie the diffuse *Cu* band 13.86
13.94		1.2		
....	3614.26			
14.42		3		
14.87		1		
15.32		1.2		⊙ has 15.34 (*Fe*). No coinc.
15.91		1.2		
17.01		2−	1−	
23.36		2+	2	At red edge of the *Fe* line 23.34. R gives 23.36
24.60		3		
24.77		1.2		
26.33		2.3	1+	Also *Fe*
28.50		1+		
28.80		1.2		
29.45		2.3		
3635.30		2	2	*Mo?* But separated from the ⊙ line 35.34 *Ti*, *Fe*
3635.57		2.3		At edge of ⊙ line 35.61 *Ti*, *Fe*
35.77		1.2		
.....	3637.40			
37.68		2−	?	⊙ has 37.69. Coinc?
38.35		2.3		
38.57		1.2		Also in *V*. Foreign line?
38.72		1.2		
40.76		2+		
41.08	{	2		
41.16				
42.37		2−		
47.03		1+		
48.75		2		
49.61		1.2		At edge of ⊙ line 49.65 (*Fe*)
50.75		1	?	
51.48		2		
53.75		1		
54.73		2+	?	Diffuse. *Mo?* ⊙ has 54.81 *Fe* .74 *Ti* 54.6 *Cu*. Very diffuse
55.21		1.2		Diffuse. *Mo?*
57.53		2.3		⊙ has 57.56 *Fe*
58.50		1		
.....	3658.69			
59.51		3.4		
61.08		2−		
61.24		1.2		
61.91		2+	?	
63.14		2	?	
63.83		1+	?	
64.45		2−		
64.98		3	1	
66.87		2+		⊙ 66.91 *Fe*
68.63		1.2	?	
69.50		2.3	1	
72.97		3		
73.38		1.2		
75.54		2		
76.15		1.2		*Fe* has 76.11 separated
76.40		2+		
.....	3676.70			
77.83		2−		⊙ has 77.83—? .76 *Fe*
79.39		1.2		
80.36		1+		
80.75	{	3.4		On each side of ⊙ line 80.80
3680.85				

Mo λ	R.	*i*		Remarks
		Mo	⊙	
3681.69		1.2		
81.88		2−		
82.12		1		
84.48		1.2		
86.27		2−		
86.72		2−		
87.12		1		
88.12		1		
88.45		2−		
89.13		2		
90.30		1		
90.72		2.3		
.....	3691.45			
92.24		1.2	?	
92.79		2−	2	*Mo?* ⊙92.79 *Fe*
93.52		2−		
95.09		3.4		
96.18		1.2	1	*Mo?* 96.17 *Fe*
3698.69		1.2		
3700.15		1.2		
01.67		1		
02.33		1+		
02.67		2		By the *Fe* line 02.63
.....	3704.60			
05.57		1+		
07.35		1..		
08.73		2−		At edge of ⊙ line 08.79
10.32		1.2		
11.68		1.2		
12.22		1.2	?	Coinc.?
13.64		2−		
14.73		1.2		
15.83		2		
16.27		2	1	
17.05		1+		
18.66		1+		
19.71		1+		
19.87		1+		
20.42		2−		
22.50		1−		
23.70		1.2		
24.00		1+		
.....	3724.53			
25.75		2+		
26.45		2		Dbl. Center. $\Delta\lambda=0.09$
27.86		3		R. gives ⊙ 27.78 (*Fe*). Wholly separated
3728.50		1.2		
3728.70		2		
30.75		1		
32.91		3	2	Double. Center
33.22		2−		
33.59		1+		
34.56		1.2		
35.80		1.2	1−	Coinc?
36.36		1+		
38.10		2+		
.....	3740.20			
40.97		1+		
42.48		2.3		
43.98		1+		
44.55		2−		
45.12		1.2		
47.37		2−	1	
48.66		2+		
51.38		2+		
52.12		1−		
55.31		2		
55.68		1		
56.02		1.2		
58.70		2+		
59.80		1.2	1	
.....	3760.68			
61.07		2−		
61.93		2−		
62.27		1.2		
63.52		2		Also *Mn.* (63.51) Coinc?
64.20		1		
64.60		1.2		
65.21		1+		
65.40		2−		
65.92		1.2		
66.58		1		
67.90		1+		
68.78		1+		
68.92		1.2		
70.66		2.3		
72.11		2+		
72.99		2+		
76.27		1+		
76.73		1+	1.2	
77.90		1.2		
.....	3778.20			
79.92		2+	?	⊙ has a faint pair. Coinc?
80.78		1−		
81.75		2.3	2	
82.35		1.2		
82.86		1		
85.19		2		
3785.67		1.2		

Mo λ	R.	*i* *Mo*	*i* ⊙	Remarks
3786.54		1		
88.42		2		
94.60		2—		
95.48		1+		
96.19		1.2		
96.45		1+		
97.20		1.2		
97.46		2—		
3798.39		10	1	Intense, broad, diffuse, reversed, with a fine absorption line; coincides with the ⊙ line
3800.28		1+		
.....	3801.82			
02.00		2.3		⊙ 01.98. Coinc ?
02.35		1+		
04.70		2		
06.15		2		
07.82		1		
08.04		1		
08.79		1.2		
10.31		1+		
10.99		1		
11.56		1.2		Sharp
12.63		2		Sharp. Faint companion to violet
14.64		1+		
15.24		1.2		
17.37		1—		
18.83		2—		
19.98		2.3		
21.09		1.2		
21.82		1		
22.14		1		
23.17		2+		⊙ has a faint band here
.....	3823.65			
24.34		1.2		
24.94		1.2		
25.50		1.2		
25.63		1+		
26.85		2.3		
27.33		2+		
29.04		3—		
29.95		1.2		
30.08		1+		
30.22		2—		
3830.98		2—		Between ⊙ lines 31.00 } 30.90 } *Fe*
3831.25		1.2		
31.95		1+		
32.26		2		
33.92		3		
34.82		1.2		
35.15		1.2		
35.49		2—	1.2	Coinc. ⊙ line diffuse
39.65		1+		
40.72		1+		
.....	3843.40			
44.09		1.2		
46.12		2+	2	Coinc. ?
46.36		1.2		
47.41		2+	2	Faint ⊙ group. Coinc.?
48.45		2+	2	Coinc.? R. gives ⊙ 48.43.—48.48 (*Ti*) separated from *Mo*
49.95		1+		
51.57		1+		
52.17		2—		
55.09		1		
56.15		1+	1.2	*Mo?*
.....	3863.53			
3864.25		10	1	Broad, diffuse, rever'd, with fine absorption line. R. gives 64.25 *Mo—C*
66.87		1+		
69.25		2.3	?	⊙ has a group here
70.62		1.2		
70.77		1.2		
73.30		1.2		Weak. At edge of ⊙ line 73.25 (*Co*)
74.34		1.2	?	Coinc.? 74.32 (*Ti*). Intensity variable? Foreign line ?
79.20		1+		
.....	3885.66			
86.98		2.3		⊙ has 86.94 (*Cr*), separated
87.87		1		
3888.15		1—		

Mo λ	R.	*i* *Mo*	⊙	Remarks
3888.36		2—		
89.06		2—	?	Coinc ?
90.88		1.2		
93.50		1+		Between the ⊙ lines 93.54—*Fe* .45 *Co?*
96.55		1.2		
97.05		1.2		
3897.68		1+		
3900.40		1—		
00.87		1		
01.95		2.3		
.....	3902.40			
03.07		10	5	Extremely strong, diffused, reversed with fine absorp'n line
07.10		2—	1	*Mo?*
08.42		1.2	1.2	*Mo?*
09.92		1.2		
11.24		1.2		Diffuse
12.10		1.2	1.2	*Mo?* 12.13 *Cr?*
13.52		1.2		
15.60		1		
16.62		1+		
17.09		2—		
17.70		2+	?	Coinc ?
17.95		2		
20.25		1—		
21.09		1+		
22.49		2—		
23.91		2		
.....	3924.67			
24.78		1		
26.00		1		
28.45		1.2	?	Coinc. ?
28.86		1.2		
28.95		1.2		
30.35		1.2		
31.57		1.2		
34.41		1.2		The *Ca* lines H and K occur with slight intensity
35.13		2		Centr. of close double
35.33		1.2		
36.30		1		
3936.89		1+		Also *Mn* Foreign line ?
3938.88		1.2		
39.30		1+		
39.65		1+		
40.50		1		
.....	3941.02			
43.19		3		
43.66		2—	1+	*Al.* 44.10 distinctly fainter than 61.57
45.41		2—		⊙ has 45.47 (*Co*) separated from *Mo*
47.00		1		
47.33		2—		
50.40		1		
51.14		2—		
51.49		1+		
51.70		1		
54.08		2		
55.66		2—		
58.76		2—		
59.03		1		
59.83		1+		
60.12		1+		*Al.* 61.57 strong
.....	3960.42			
63.68		1.2		
64.14		2—		
65.89		1.2		
66.40		1.2		
68.91		2—		
69.17		1		
71.54		1.2		
73.10		1+	?	
73.92		2+		
74.09		2		
78.08		2—		
79.40		2—		
80.37		2		
80.87		1.2		
81.80		1.2		
......	3981.92			
82.22		2		
84.92		1+		
85.88		1.2		
86.45		2+	1	
91.55		2—	1	
92.02		2—		
93.22		1.2	1.2	Coinc. *Mo?*
94.06		2—	?	Perhaps Coinc.
94.79		1		
95.66		1+		Weak
3998.45		2—		

Mo λ	R.	*i* *Mo*	*i* ⊙	Remarks
4000.55		2−		⊙ line 00.61 (*Fe*) between these two *Mo* lines
00.67		2		
03.62		1+		
......	4003.91			
05.86		1	2	Coinc. *Mo?* Also *V*. Other strong *V* lines are lacking
06.23		2		
06.85		1		
07.62		1		
08.21		1+		
09.53		2		
12.12		2−		Diffuse. *Mo?*
12.42		1		
12.68		1		
12.97		1−		
16.86		1+		
17.55		1.2		
......	4018.42			
19.32		1		
20.59		1.2		⊙ has 20.64—*Fe* .55 *Sc*
21.19		2		
25.64		1.2		
27.07		1+		
28.80		1.2		
31.06		1+		
31.60		1		
32.65		1.2		At red edge of ⊙ line 32.61 (*Fe* by R.; *V* by H.)
34.11		1	1−	
36.83		1+		
37.95		2−		
38.26		2	1−	
......	4040.79			
41.30		1.2		
43.05		2		
43.44		1		
43.91		1.2		
47.07		1		
47.56		1−		
47.75		1−		
49.78		1		
50.27		1+		
4051.35		1+		

Mo λ	R.	*i* *Mo*	*i* ⊙	Remarks
4056.18		2		56.22 *Cr* 56.13 *Fe*
57.61		1+		
57.77		1.2		Also *Ti* (57.76)
......	4059.08			
59.79		2−		
62.24		2.3		
66.52		2−	2	Coinc. *Mo?* 66.52 *Co*
67.88		1+		
70.05		3+		Hard to separate. Total intensity = 4
70.17		2		
75.43		2	1	
75.72		2−		
76.35		2		
76.69		1.2		Between the ⊙ lines 76.80 .64
78.25		1+		
......	4080.00			
81.62		3		
81.94		2−		
84.54		3	?	Perhaps Coinc
86.10		2		At red edge of ⊙ line 86.13
89.90		1.2		
93.32		1+		
94.63		1−		
96.98		2+		
4098.91		2+		
4102.33		2.3	1	
03.94		1.2		
......	4104.20			
05.27		2+		At edge of ⊙ line 05.31 *V*
05.72		2−		
07.63		3	3	⊙ has 07.65 *Ce*, *Fe*, *Zr* separated from *Mo*. *V* has 07.64
08.30		1.2	1.2	R. gives ⊙ 08.29. *Mo?*
10.46		1		
10.88		1+		
12.29		1		
13.77		1+		
15.08		2−	2	*Mo?*
19.12		2		At edge of ⊙ line 19.05 (*Fe*)
4119.81		1+	1	

Mo λ	R.	i Mo	i ⊙	Remarks
4120.26		3		
22.55		1		
23.83		2		
24.72		2		
......	4126.34			
28.46		2+		
29.02		2−		
32.07		2−		
32.41		2−		Intensity variable. Is it *Mo?*
32.90		1		
33.18		1+		
35.37		1		
35.55		1+		
37.10		1+		
38.35		1.2		
38.72		1.2		
39.72		1+		
42.28		1+		
43.73		4		
......	4147.84			
48.88		1+		
49.14		2.3		
49.90		1		
52.07		2−		At edge of ⊙ line 52.11
55.47		2.3		
55.77		2.3		
57.59		2.3		
58.27		1+		Overlies a diffuse band at 58.10. *Cu?*
60.44		1+		
62.85		2.3		Does not coincide with ⊙ 62.83
64.26		1.2		
65.94		1		
66.47		1.2		
68.68		1.2		
70.01		2−		⊙ has 69.93 (*Fe?*)
70.55		1		
......	4171.07			
71.27		1.2		At edge of ⊙ line 71.21 (*Ti*)
71.65		1+		
75.32		1	1.2	
77.09		1.2	1+	
77.45		2		
78.45		2		
4178.72		1		
4180.12		1.2		
80.69		1.2		
81.24		2		Center of close double
84.33		1		
84.59		1.		
85.98		3	1	
86.97		2−	1+	
88.49		4		
......	4192.73			
94.20		1		
94.74		2.3		
4199.82		1		
4200.02		1		
00.76		1.2	1.2	
01.35		1+		
01.50		1.2		
02.42		1		
04.80		1.2		
06.00		2		
07.42		1+		
07.75		1+		
08.97		1		
09.84		1	1	
10.39		1		
11.23		2−		
....	4213.81			
14.24		1.2		
17.02		1		
19.20		1+		
19.55		2		Appears to lie between the ⊙ lines 19.52 and 19.58. These lines belong to *Fe*
20.17		1		
22.59		1.2		
23.15		1.2		
24.10		1		
24.93		1		
25.10		1		
26.44		1.2		
32.75		3+		
33.68		1.2		
35.23		1.2		
....	4236.11			
39.25		2−		
39.37		2−		
40.26		2		Also *V*
40.48		2		
41.03		2.3		
4242.97		1.2		

Mo λ	R.	*i*		Remarks
		Mo	⊙	
4244.95		1.2		Diffuse. Double ?
46.19		2.3		At edge of ⊙ line 46.25 (*Fe*). K. R. give 46.20
50.87		1.2		
51.58		1		
52.03		2.3		
52.69		1+		
53.77		1+		
.....	4257.82			
58.85		1+		Between two ⊙ lines
60.52		1.2		
60.85		1.2		⊙ has 60.89. Separated
61.17		1		
61.63		1.2		
64.81		1+		
66.27		2−		
68.25		2−	2	Coinc. *Mo ?*
69.44		2.3	1	
72.24		1.2		
73.23		1.2		Sharp
74.22		1+		
.....	4274.96			
75.86		1+	?	
77.08		3		
77.38		3	?	R. gives ⊙ 77.38.
77.58		2	?	R. gives ⊙ 77.54 *Zr.* Coinc ?
79.19		1+		
80.17		1+	1.2	Coinc. *Mo?*
82.00		2−		
84.77		3		Diffuse. *Mo?*
87.26		2−		
88.82		3+		
89.56		2+		At edge of ⊙ line 89.50 (*Ca*)
91.39		2−		
92.34		3		
93.42		3		
94.07		3		
.....	4295.91			
4296.35		1.2		
4301.45		1.2		
04.20		1.2		
4305.10		2−		

Mo λ	R.	*i*		Remarks
		Mo	⊙	
4308.85		1		
10.58		2−	2.3	⊙ has 10.63 .54
12.98		1.2		
13.16		1.2		
13.74		1+		
15.60		1		
18.13		2.3		
18.46		1		
......	4318.82			
22.17		2−		
22.66		1+		
24.72		1		
25.44		1		
26.33		3		
29.50		1+		
29.82		1.2		
30.27		1+		
32.68		1+		
33.40		1		
34.65		1		
35.00		2	1	⊙ has a faint triple; coincidence is with the middle component
36.38		1+		
38.73		1		
38.90		2−		
39.42		1+		
40.02		1.2		
40.93		2−		
41.61		2+		
42.16		1		
.....	4344.67			
44.86		1.2		
46.40		1+		
49.41		1−		
50.53		3−		
53.48		2−		
54.88		1−		
57.50		1.2		
62.20		1.2		
62.87		1+	1.2	Coinc. *Mo?*
63.21		1−		
63.82		1.2		
64.65		1.2		
64.76		1+		
64.90		1+		
66.73		2		
.....	4368.07			
69.23		2.3		
4370.33		1		

Mo λ	R.	*Mo* ^{i}	⊙	Remarks
4372.31		1+		
73.52		1+		
75.07		1+		
75.21		1.2		
76.87		1+		
80.47		2+		
80.80		1.2		Sharp
81.36		1+		
81.82		4		
82.61		2−		
86.10		1+		
.....	4388.06			
88.49		1		
89.76		1		
91.71		1.2		
92.32		1.2		
94.49		1.2		
94.67		1.2		
96.55		1		
96.83		2		Sharp
97.02		1		
97.48		2+	?	Perhaps coinc.
98.68		1		
4402.67		2−		
03.07		2+		
04.71		1.2		Sharp
07.04		1+		
09.61		1		
10.15		2−	1	Coinc.?
.....	4410.68			
11.76		2.3		
11.90		3		
12.96		2+		
17.40		1		
20.91		1		
22.23		1.2		
23.24		1+		A line here also in *Ni*. Not given by R.
23.79		2.3		
24.40		1		
26.86		2.3		
28.39		1		
29.32		1		
.....	4433.39			
33.68		1.2		Sharp
37.06		2−		
37.35		1+		
39.15		1+		Sharp
42.37		2.3		Sharp
43.25		2		Sharp
44.21		1+		Diffuse. *Mo?*
46.62		2−		Sharp
4447.41		1.2		

Mo λ	R.	*Mo* ^{i}	⊙	Remarks
4449.92		3		
52.77		1.2		
.....	4454.95			
57.55		3.4		
58.84		1.2		
60.80		2−		
64.96		3−		⊙ has 64.94 *Fe* separated
68.28		1+		
68.46		3		
71.85		1.2		
72.23		1.2		
73.37		2.3		
74.78		4		
75.82		2+		
.....	4476.22*			
85.16		2.3		
87.23		2+		
89.17		1.2		
90.37		2		
91.46		3		
92.00		1		
92.24		1		
94.27		1+		
4499.62		2−		
4501.44		2		⊙01.42 *Ti* separated
06.13		} 3		
06.22				
06.86		2		
.....	4508.45			
12.32		2.3		
15.20		1.2		
15.36		2−	1	Coinc.?
17.30		3+	1.2	Coinc. 17.28 *Co*
17.58		2		
18.61		1+		
22.37		2+		
24.53		3		
25.50		1−		
25.56		2+		
28.77		2.3	4	Diffuse. Coinc. *Mo?* 28.80 *Fe*
29.59		2.3		Sharp
.....	4533.42			
34.63		2		Diffuse. *Mo?*
35.00		2+		Diffuse; broad. *Mo?*
35.56		2	?	Probably a ⊙ line
37.00		3+		
38.60		1		
4539.84		1		

* Double 76.253, 76.185. Center.

Mo λ	R.	*i*		Remarks
		Mo	⊙	
4541.75		2—		
53.00		1		
53.40		1.2		
53.52		1.2		
54.00		2	3.4	*Mo?*
.....	4554.21			
58.30		2.3	1	Coinc.
58.92		1.2		
59.94		1+		
60.32		2+		Sharp. At edge of ⊙ line 60.27 (*Fe*). K. R.: 60.33
67.57		1—		
67.87		2+		
69.21		1+		
70.30		2		Sharp
70.78		1+		Sharp
74.66		1+		
74.80		1		
75.36		1—		
76.05		1+		
76.70		3—		Sharp
77.97		1+		Sharp
78.06		1		
.....	4578.73			
79.92		1		
82.52		1+		
82.69		1+		
86.25		1+		
86.75		1+		
86.98		1+		
87.61		1		
88.33		1.2		Diffuse. *Mo?*
90.55		2		Diffuse. *Mo?*
92.40		1.2		Sharp
93.84		1		
95.35		3		
98.07		1+	1.2	Coinc. *Mo?*
98.44		1+		
4599.35		2—	?	Probably a ⊙ line
.....	4603.13			
4603.78		1—		
08.32		1		
08.90		1+		Sharp
10.07		3	1	Coinc.
11.03		1+		
11.36		2—		Sharp
14.04		1		
16.81		1+	1.2	Probably not *Mo*
17.82		1		
18.15		1+		Sharp
21.57		2.3		Sharp
4623.66		1.2		Sharp
4624.44		2		Diffuse. *Mo?*
.....	4625.23			
26.67		3.4		26.74 *Mn* separated. *V* 26.67 similarly
27.70		2.3	1	⊙ line extremely faint. Coinc.?
30.20		2—		Sharp
32.75		1		
35.22		1		
41.12		1—		
41.78		1—		
42.90		1.2		
.....	4646.35			
48.02		2		Sharp
49.28		1.2		
51.25		2—		
52.47		2		Diffuse, probably not *Mo*
56.57		1		
57.67		1		
62.11		2.3		Does not coincide with ⊙ 62.15
62.95		3	1	
63.31		1+		
65.59		1+		
.....	4667.77			
69.00		1+		
72.11		3—		
73.24		1		
75.91		1—		
.....	4679.03			
81.24		1+		
81.82		1		
82.44		1—		
84.04		1.2		
84.54		1+		
86.01		2—		
86.28		2—		
88.41		2.3		Separated from 88 46 (*Fe*). R. gives 88.36 (*Fe*)
91.05		2—		
92.19		1+		
92.89		1—		
93.55		1—		
96.06		1+		
4696.71		1.2		
.....	4700.34			
4700.71		2—		

Mo λ	R.	*i* *Mo*	⊙	Remarks
4706.25		2		Also *Cr*
06.40		1+		
07.44		3.4	2.3	Rowland gives 07.46 (*Fe*). $\lambda_{Fe} > 07.46$? K. R. 07.52
08.43		3−		
10.16		1		
14.69		2−		
16.88		1+		
18.13		2.3		
19.08		2		
.....	4722.34			
23.27		1.2		
23.50		1		
25.55		1+		
29.36		3.3		
31.64		3.4		
34.34		1+		
35.51		1		
36.84		1+		
40.36		1		
40.58		1		
.....	4741.72			
49.06		1−		
49.35		1−		
49.61		1−		
50.60		2.3		Sharp
51.31		1		
53.56		1		
56.06		1		
58.71		2.3		
60.39		4		Faint lines near by. *Mo?*
.....	4764.11			
64.64		2		Sharp
73.47		1.2		
73.64		2+		
74.42		2−		
75.87		2.3		
76.54		3	1.2	R. gives ⊙ 76.55 (*Co*). Also in *V* as strong line, $i=3$
78.09		1		
83.16		2.3	1	Coinc.?
.....	4783.61			
84.64		1		
85.34		2.3		Sharp
4786.68		2		At edge of ⊙ line 86.73 (*Ni*). *V* has 86.70

Mo λ	R.	*i* *Mo*	⊙	Remarks
4787.83		1		
88.39		1+		
92.96		2		
93.60		2		Sharp
94.03		1.2		
94.81		1+		
96.75		2.3		Sharp
.....	4798.45			
4805.13		1+		
05.78		2−		
08.29		2−		At violet edge of the ⊙ line 08.32 (*Fe*)
08.68		1+		
11.28		2.3		
14.68		1+		
17.92		2−		
.....	4817.99			
19.47		3		
22.62		1+		
23.16		1−		
28.67		2−		Sharp
30.15		1+		
30.73		3		Very sharp
33.13		1.2		
34.16		2−		
35.98		1−		
38.35		1		
.....	4839.73			
39.82		1		
45.38		1+		
50.05		1−		
51.92		1		
58.44		1.2		
.....	4859.93			
60.28		1.2		
60.99		1		Faint companion to red
66.07		1−		
68.23		3		
69.43		2		
.....	4871.00			
75.73		1+		At edge of the ⊙ line 75.67 (*V*)
78.59		1.2		
86.70		1+		
89.44		1+		
94.65		1−		
.....	4896.62			
97.50		1+		
4899.81		1−		
4904.03		2.3		
4907.65		1+		

Mo λ	R.	i *Mo*	⊙	Remarks
4909.41		1+		
.....	4917.41			
25.08		1—		
26.42		2—		
26.65		2—		
31.42		1—		
33.30		2		
33.99		1		
.....	4936.02			
41.90		2+		
50.83		2.3		
52.20		1—		
56.83		1—		
.....	4957.78			
57.78		3		R. gives 57.78 *Fe*. The lines are separated, however, and λ > λ *Mo*. Probably it should be λ_{Fe} =57.88. Kayser and Runge have 57.87
64.42		1.2		
64.63		2—		
75.58		1		
76.23		1—		
79.32		2.3		
.....	4980.35			
4995.55		1—		
5000.13		2+		
.....	5002.98			
14.80		1+		
16.99		2.3		
20.07		1—		
.....	5025.03			
29.21		2		
30.96		2—		
39.12		1—		
.....	5044.39			
46.73		1		
47.90		2		
55.22		1.2		
58.30		1		
60.07		2.3		
62.76		1+		
.....	5064.84			
80.23		2.3		
81.49		1		
.....	5084.28			
84.47		1—		
5090.80		1		
5091.17		1.2		
91.56		1		
92.40		1+		
92.96		1		
96.11		1.2		
96.85		2+		At edge of the ⊙ line 97.67
97.71		2.3		
5098.27		1.2		
5100.58		1—		
.....	5105.72			At edge of the ⊙ line 09.83 (*Fe*)
09.90		2+		
15.21		2		
15.86		1—		Sharp
17.18		1.2		
22.00		1		
.....	5123.90			
24.03		1+		
26.94		1		
35.17		1		
41.47		1+		
.....	5146.66			
48.65		1		
55.48		1—		
63.40		2+		
.....	5165.59			
67.98		2		
71.33		3		
73.14		3		In the shade of b_2
74.35		3		
5180.44		1.2		
.....	5186.07			
5200.37		2—		
00.97		1		
.....	5204.72			
12.08		1		
19.62		1.2		
.....	5225.70			
31.27		1+		
32.58		1—		
34.47		2—		
38.41		3		Companion to violet
41.09		3		
.....	5242.66			
43.01		2		
45.71		2—		
59.23		2+		
61.35		2—		
.....	5266.73			
72.00		1—		
76.50		1—		
5279.85		2—		

Mo λ	R.	*i* *Mo*	*i* ⊙	Remarks
5281.07		2+		
.....	5288.71			
92.30		1.2		
93.65		1		
5295.67		1.2		
5306.49		1−		
.....	5307.54			
14.13		2−		
18.20		1		
20.14		1		
24.70		1−		
27.35		1		
.....	5328.75			
55.12		2−		
55.76		1+		
56.70		2−		
60.76		4.5		
64.50		3.4		
67.30		2−		Diffuse
.....	5370.17			
72.63		1+		
88.94		1		
.....	5389.68			
94.75		2		Sharp. ⊙ has 94.91 84 } *Mn*
5397.63		1.2		
5406.64		1.2		
11.31		1−		
14.95		1−		
.....	5415.42			
17.64		1.2		
26.24		1		
27.14		1.2		
27.80		1		
31.27		1+		
.....	5434.74			
35.91		2+		
37.97		2.3		
39.95		1+		
47.86		1−		
48.78		1−		
50.73		2.3		
53.27				
.....	5455.75			
56.71		2+		
65.83		2−		
73.64		3		
76.18		2		
.....	5477.12			
88.91		1−		
5490.54		2		
5492.43		2−		
94.06		2		
97.18		1.2		Diffuse
98.76		2−		Sharp
5499.77		1+		Diffuse
5501.78		2		Sharp
02.18		2−		
03.82		1.2		
06.75		6		
.....	5507.00			
11.77		1+		
17.73		1		
20.32		1.2		
20.93		1.2		
.....	5525.76			
26.81		2		
27.27		2		
32.00		1+		
33.26		6		
34.85		1		
39.67		2		Sharp
41.93		1+		Sharp
43.38		2+		Sharp at violet edge of ⊙ line 43.41 (*Fe*)
.....	5544.16			
44.78		2		Sharp
52.47		1+		
.....	5555.12			
56.55		2.3		
57.02		2		
62.74		1		
63.65		1		
64.34		2−		
68.88		2.3		
69.75		2		
70.69		6		
75.47		2+		
.....	5576.32			
89.02		2	2.3	Coinc.? At edge of ⊙ line 88.98 (*Ca*)
91.84		2−		
.....	5594.69			
5596.62		1.2		
5601.31		1.2		
08.90		2		
09.53		2+		
09.80		1		
11.20		3		
13.37		2		
.....	5615.88			
18.69		2−		
5619.03		1.2		

Mo λ	R.	i Mo	☉	Remarks
5619.63		2—		
32.74		4		
.....	5634.17			
35.14		2.3		
42.05		1—		Near the ☉ line 42.11 (*Ni*)
43.47		1—		
50.40		4		
51.54		1+		
52.12		1.2		
52.47		1+		
.....	5657.72			
64.65		1.2		
67.57		1.2		
72.35		1+		
73.92		2+		
74.77		2.3		
.....	5675.65			
78.18		2.3		
83.20		2+		
87.93		1+		
89.39		4.5		Companion to red
.....	5693.86			
94.64		1+		
95.10		1		
95.66		1—		
96.30		1.2		
98.53		2—		
5699.57		2+		
5702.39		1.2		
05.97		3		
08.28		1+		
.....	5711.31			
12.05		2		Near the ☉ line 12.09 (*Ti*)
19.55		1—		
20.45		1—		
22.98		3.4		
29.03		2—		
29.77		2		
30.17		2—		
31.58		1—		
.....	5731.98			
34.32		2—		
35.55		1—		
38.40		1—		
39.93		1		
41.96		1		
47.08		1—		
5747.93		1+	1+	

Mo λ	R.	i Mo	☉	Remarks
5751.67		4.5		
.....	5754.88			
57.80		1		
65.57		1—		
66.79		1—		
67.63		1—		
70.02		1+		
71.33		1+		
.....	5772.36			
74.85		1.2		
78.46		1		
79.65		2		
80.38		1		
80.96		1—		
83.54		2—		
85.99		1		
.....	5788.14			
5792.10		4		
5800.72		2—		
02.95		2+		
06.46		1—		
08.54		1+		
09.30		1		
.....	5809.44			
14.14		1		
15.76		1+		
16.00		1		
21.00		1—		
25.28		1		
25.50		1.2		
.....	5831.82			
35.87		1—		
40.25		1—		
.....	5848.34	...		
49.16		1.2		
49.99		2		
51.80		2		
58.52		4		
61.66		1—		
.....	5866.67			
69.05		1—		
69.57		2		
76.90		1		
81.85		1—		
.....	5883.07			
83.11		1—		
88.61		4		
91.89		1		
.....	5893.10			
5893.67		2		

SYSTEMATIC ERRORS IN THE MEASUREMENT OF SPECTRUM PLATES.

In the treatment of the photographic plates I have always followed the procedure of dividing the metallic lines into small groups, of from fifteen to twenty tenth-meters' range, and referring them to two lines of Rowland's list, simple if possible, from which the wave-lengths could be obtained with sufficient precision by linear interpolation; but, for the sake of controlling still further the values so obtained, a solar line is commonly also measured in every group, and its wave-length determined with the metallic lines must then also agree with the value given by Rowland. To show the accuracy with which this agreement was attained in these measures, I give the following table containing a series of such solar lines together with a comparison with Rowland's values:

H.	R.	H.– R.	H.	R.	H.– R.	H.	R.	H.– R.
3717.523	17.539	–0.016	4070.912	70.930	–0.018	4374.621	74.628	–0.007
29.954	29.952	+ 002	71.893	71.908	– 015	4395.198	95.201	– 003
44.253	44.251	+ 002	76.102	76.101	+ 001	4425.598	25.608	– 010
66.799	66.801	– 002	4098.327	98.335	– 008	4449.325	49.313	+ 012
86.300	86.314	– 014	4100.878	00.901	– 023	4571.261	71.275	– 014
3792.472	92.482	– 010	14.605	14.606	– 001	4598.286	98.303	– 017
3852.710	52.714	– 004	18.696	18.708	– 012	4636.025	36.027	– 002
73.900	73.903	– 003	36.675	36.678	– 003	4691.573	91.602	– 029
3892.073	92.069	+ 004	56.962	56.970	– 008	4772.998	73.007	– 009
3916.868	16.879	– 011	63.802	63.818	– 016	4810.710	10.724	– 014
33.822	33.825	– 003	4185.040	85.058	– 018	5234.787	34.791	– 004
41.897	41.878	+ 019	4202.197	02.198	– 001	5250.808	50.817	– 009
48.227	48.246	– 019	04.138	04.132	+ 006	5322.234	22.227	+ 007
52.099	52.103	– 004	22.363	22.382	– 019	5353.575	53.571	+ 004
68.611	68.625	– 014	25.605	25.619	– 014	5445.255	45.259	– 004
3996.118	96.140	– 022	48.381	48.384	– 003	66.582	66.609	– 027
4007.409	07.429	– 020	67.108	67.122	– 014	5497.723	97.735	– 012
10.298	10.327	– 029	4288.319	88.310	+ 009	5560.430	60.434	– 004
30.323	30.339	– 016	4307.914	07.907	+ 007	5638.477	38.488	– 011
45.977	45.975	+ 002	08.075	08.081	– 006	5662.737	62.744	– 007
50.820	50.830	– 010	37.193	37.216	– 023	5701.766	01.772	– 006
66.508	66.524	– 016	51.200	51.216	– 016	5763.200	63.218	– 018
			58.657	58.670	– 013	5816.558	16.601	– 043

The first fact which attracts attention in this table, aside from the generally very small amount of the differences H.— R., is that with few exceptions they are negative, and hence my wave-lengths are throughout too small. Accordingly, there is a systematic difference or a personal equation between myself and Rowland, the amount of which, —0.009 tenth-meters, is the mean of the above differences. If this is added, with the reversed sign, as a systematic correction to the differences H.— R., they then take the character of accidental errors of observation, from which the probable error of a wave-length measured by me, referred to Rowland's system, comes out 0.007 tenth-meters, an accuracy which must be regarded as in fact very satisfactory.

It may be regarded as certain that in general an equal precision is not attained for the metallic line; but if we should in this case double the probable error, it would not then reach the value 0.02, as already remarked; or, in other words, in all probability the measurements are not inconsiderably more accurate than I have hitherto considered myself justified in assuming.

In regard to the origin of the above-mentioned systematic difference between my measures of the solar lines and those of Rowland—which difference, by the way, appears of exactly the same magnitude in the measures of the arc-spectrum of tungsten which I have just concluded—we can hardly assume that it is to be sought in other than purely physiological peculiarities, which cause a certain dependence of the setting of the thread of the microscope on the spectral line upon the direction from which the settings are made. In my measurements this direction is always apparently from left to right in the field of view of the microscope, which is also the direction of decreasing wave-lengths. In order to get more accurate knowledge as to how far this suspicion is justifiable, I measured a number of solar lines used in connection with the tungsten spectrum after reversing the direction of the plate, hence from violet toward red; I thus obtained values which differ from the previous ones only slightly, but nevertheless systematically. These measures are contained in the first two columns of the following table, which gives also the differences of the two series of measures, their mean, and a comparison with the corresponding determinations by Rowland.

An examination of the third column of this table leaves us hardly room to doubt that there is a difference, distinct although very small, between the two series, amounting in the mean to 0.006 tenth-meters. In the first position of the plate the wave-lengths are accordingly too small by 0.003 tenth-meters, in the second position just as much too large. We have therefore

I	II	II − I	$\frac{I+II}{2}$	R.	H. − R.
4015.753	763	+ 0.010	758	760	− 0.002
25.962	972	+ 010	967	972	− 005
52.078	083	+ 005	080	070	+ 010
70.409	419	+ 010	414	431	− 017
4087.243	245	+ 002	244	252	− 008
4106.583	576	− 007	580	583	− 003
25.771	781	+ 010	776	776	000
42.017	025	+ 008	021	025	− 004
63.796	815	+ 019	806	818	− 012
4182.916	914	− 002	915	922	− 007
4201.078	075	− 003	077	089	− 012
20.493	506	+ 013	500	509	− 009
39.501	511	+ 010	506	525	− 019
58.475	490	+ 015	482	477	+ 005
74.332	341	+ 009	336	348	− 012
4299.140	147	+ 007	143	149	− 006
4307.908	917	+ 009	912	907	+ 005
08.078	080	+ 002	079	081	− 002
13.029	038	+ 009	033	034	− 001
27.269	263	− 006	266	274	− 008
44.439	451	+ 012	445	451	− 006
68.054	067	+ 013	060	071	− 011
4379.377	394	+ 017	385	396	− 011
4400.548	546	− 002	547	555	− 008
17.858	868	+ 010	863	884	− 021
43.358	356	− 002	357	365	− 008
56.777	780	+ 003	778	794	− 016

obtained only a partial explanation of the systematic difference of my wave-lengths from Rowland's, since a systematic difference of −0.006 still remains after the values have been freed from the effect of the direction of measurement. If we could assume a personal error, of a similar sort but in opposite direction, for the measures of Rowland, everything systematic in the mutual differences of our measures would be eliminated, and they could be regarded purely as errors of observation. There seems to me to be nothing *a priori* against such an assumption.

Inasmuch as the probable error of the wave-lengths I determined in the solar spectrum amounts, as above stated, to ± 0.007 tenth-meters, or almost exactly the mean difference of series I and II, we might question the validity of the assumption of the slight effect of the direction in which the settings were made on the solar lines. The entirely similar appearance of the objects set upon — the line to be measured and the normal line — would seem to exclude every sort of systematic difference in the mode of making the setting. However, since the differences of the two series are, with few exceptions, in the same sense, as appears from the third column, it seems to me we can hardly deny the actual presence of such an effect, although for one I am unable to produce any sufficiently satisfactory explanation for it.

Accordingly, if the observation of such similar objects as the solar lines appearing on a dark background gives evidence of an effect, however small, of the direction in the which the setting is made, we should certainly expect in advance a similar and more marked effect when the lines of the metallic spectrum were to be referred to those of the Sun. We should much sooner assume a difference in the mode of setting according to the position of the image in the case of setting the thread first on the bright solar line on a dark field and then upon the dark metallic line in a bright field, and this has been fully confirmed. In order to investigate the question further, I repeated the measures with the plate reversed for certain groups of lines of tungsten, which I had already measured in the usual direction of decreasing wave-lengths from left to right in the field of view of the microscope. The following table, in which the wave-lengths obtained in the two positions of the plate are given under the heading I and II, shows the results of these measurements:

I	II	II—I	I	II	II—I
4411.871	.834	—0.037	4425.064	.030	—0.034
12.347	.343	— .004	26.087	.052	— .035
13.173	.142	— .031	27.533	.508	— .025
14.042	13.987	— .055	28.663	.607	— .056
15.233	.246	+ .013	32.379	.314	— .065
15.891	.845	— .046	35.903	.874	— .029
18.609	.584	— .025	37.070	.070	.000
18.967	.934	— .033	38.469	.441	— .028
19.429	.387	— .042	39.904	.845	— .059
20.627	.608	— .019	42.004	41.976	— .028
21.168	.135	— .033	44.650	.592	— .058
22.010	21.958	— .052	45.324	.297	— .027
			49.182	.164	— .018

We see that here also a systematic differance of the appreciably larger amount of 0.033 tenth-meters appears, the wave-lengths being measured too large by 0.016 in the first position, and as much too small in the second. In the first position of the plate the left side in the field of view was toward larger wave-lengths, and hence it follows that in the two cases the setting of the thread on the metallic lines was systematically somewhat too far toward the left in respect to the settings on the solar lines. This physiological difference in the *Auffassung* of the two different kinds of spectral lines is so pronounced as to leave no doubt as to its reality. This systematic correction or personal equation in my measures of metallic spectra is decidedly larger than that just discussed in the case of the solar lines, but it is also only of about the same magnitude as the probable error of the wave-lengths of the metallic lines, and consequently of no great significance. It has not been taken into account in the above catalogue of the lines of molybdenum, since in its determination the plates of tungsten and not those of molybdenum were employed.

The personal equation in the measurement of photographic plates of spectra here described has also been noticed elsewhere. In his measurements of stellar plates for the determination of radial velocities, Reese,[1] of the Lick Observatory, found that his settings on the dark lines of the metallic comparison spectrum were systematically somewhat too far toward the right in the field of view of the microscope in comparison with the settings on the light lines of the star, producing a systematic correction of about 1 km. This is evidently the same phenomenon that occurs in my measurements, except that it occurs in the opposite sense, which is not at all surprising in view of the wholly personal character of the phenomenon. We may remark, as an odd coincidence, that the magnitude of the personal equation is the same in the two cases. If the above measurements had been made for determining radial velocities, a variation in wave-length of 0.016 tenth-meters would easily be found to correspond in the region of spectrum considered to a change of velocity of 1.08 km.

COMPARISONS WITH THE INVESTIGATIONS OF THE SPARK SPECTRUM BY EXNER AND HASCHEK.

It has already been indicated above that, while the arc-spectrum of molybdenum has hitherto remained practically unknown,

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[1] *Lick Observatory Bulletin* No. 15; ASTROPHYSICAL JOURNAL, 15, 142, 1902.

its spark spectrum has recently been subjected to a thorough examination in the portions affecting common photographic plates by Exner and Haschek in the course of their similar investigations of all the chemical elements. Since it was the primary purpose of these investigations to establish a basis for future mineralogical researches, the greatest accuracy of the determinations of the wave-lengths was less important than the most rapid and convenient possible method of operation. Accordingly the authors determined the wave-lengths by simply projecting a thirtyfold enlargement of the plate upon a scale graduated to half-centimeters, on which, after the adjustment of the standard lines, the wave-lengths of the remaining lines were obtained by a single reading. With the enlargement employed, the 5 mm scale divisions represent tenth-meters, and accordingly the reading had to be accurate only to 0.5 mm in order to attain the accuracy of 0.1 tenth-meters originally sought for. It might, however, seem questionable in how far this method of observation can be protected from systematic errors. In order to obtain definite data on this point, I have, for the 600 lines of molybdenum common to our catalogues, taken the means of the differences of the wave-lengths by tens, and have thus obtained the following mean deviations for the portions of spectrum given:

λ	H.—E.H.	λ	H.—E.H.	λ	H.—E.H.	λ	H.—E.H.
3510	+0.09	3740	+0.07	3994	+0.14	4318	+0.03
3530	+ .07	3757	— .02	4020	+ .16	4333	+ .01
3553	+ .09	3770	— .02	4040	+ .13	4357	+ .05
3568	+ .12	3785	+ .02	4056	+ .04	4381	+ .05
3585	+ .12	3800	— .01	4090	+ .01	4400	— .08
3603	+ .06	3812	+ .05	4115	+ .03	4425	— .09
3617	+ .02	3825	+ .03	4134	— .03	4450	— .07
3630	+ .02	3837	+ .02	4152	— .06	4475	— .10
3650	.00	3856	+ .02	4177	+ .12	4502	— .05
3662	+ .04	3875	+ .03	4200	+ .08	4529	— .02
3677	+ .07	3900	+ .06	4225	+ .05	4558	— .02
3692	+ .08	3918	+ .07	4248	+ .08	4565	.00
3707	+ .11	3935	+ .11	4265	.00	4607	+ .06
3720	+ .08	3955	+ .10	4280	— .05	4640	+ .15
3730	+0.11	3980	+0.13	4295	—0.05	4684	+ .19

We may safely conclude from these figures that the accuracy sought is in general attained; but a certain periodicity is revealed in the way the figures run, which would confirm the suspicion expressed above if there were not other circumstances which would appear to throw the systematic element of the deviation rather upon the plates themselves than upon the adjustments of the enlarged images on the scale and the reading. In the course of their further investigations Exner and Haschek have, in fact, found that in the method employed at first of photographing the comparison spectrum in juxtaposition to the spectrum under investigation by successive exposures, there occurred small displacements of the two spectra in respect to each other which were beyond checking, due to an insufficient stability in the mounting of the spectrograph. The injurious effect of these displacements could be avoided only by photographing the iron comparison spectrum simultaneously with the spectrum under investigation as an impurity of it. With the use of such plates new wave-lengths were obtained by projection in the same manner as before for the stronger lines of the metals previously investigated, including molybdenum. The following table gives the comparison of these new wave-lengths with mine:

H.	E.H.	Δ	H.	E.H.	Δ	H.	E.H.	Δ
3524.76	3524.70	+0 06	3786.54	3786.43	+0.11	4269.44	4269.43	+0.01
37.41	37.40	+ .01	98.39	3798.35	+ .04	77.08	77.00	+ .08
85.74	85.78	− .04	3864.25	3864.25	.00	77.38	77.43	− .05
3596.54	3596.51	+ .03	3903.07	3903.07	.00	79.19	79.15	+ .04
3612.15	3612.27	− .12	41.62	41.60	+ .02	88.82	88.78	+ .04
14.42	14.43	− .01	3986.45	3986.32	+ .13	92.34	92.25	+ .09
35.30	35.29	+ .01	4062.24	4062.20	+ .04	4293.42	4293.33	+ .09
51.48	51.30	+ .18	70.11	70.05	+ .06	4326.33	4326.30	+ .03
58.50	58.48	+ .02	81.62	81.60	+ .02	63.82	63.75	+ .07
80.80	80.82	− .02	4084.54	4084.51	+ .03	4381.82	4381.77	+ .05
84.48	84.32	+ .16	4107.63	4107.61	+ .02	4411.90	4411.82	+ 08
88.45	88.42	+ .03	19.81	19.75	+ .06	33.68	33.62	+ .06
3692.79	3692.82	− .03	20.26	20.25	+ .01	49.92	49.91	+ .01
3702.67	3702.70	− .03	22.55	22.45	+ .10	57.55	57.50	+ .05
17.05	17.10	− .05	43.73	43.70	+ .03	74.78	74.72	+ .06
42.48	42.45	+ .03	85.98	86.00	− .02	4491.46	4491.43	+ .03
44.55	44.55	.00	4188.49	4188.50	− .01	4517.30	4517.30	.00
55.68	55.63	+ .05	4209.84	4209.82	+ .02	17.58	17.50	+ .08
3782.35	3782.17	+ .18	32.75	32.80	− .05	24.53	24.50	+ .03
			44.95	44.90	+ .05	4537.00	4536.98	+ .02
			4250.87	4250.82	+ .05	4610.07	4610.00	+ .07

We see that, in fact, not only a far better agreement is attained, but that also the former periodic variation of the differences can no longer be recognized. It therefore appears probable that these variations were produced by the above-mentioned small mutual displacements of the spectra, which occurred first toward one side and then toward the other in the plates of the different portions of the spectrum; and it would appear accordingly that no systematic errors of *this sort* are to be feared for the direct method of reading in itself. The prevalence of a positive sign of the differences indicates, however, a small systematic deviation averaging +0.03 tenth-meters,[1] which is doubtless of personal origin, and may be partially explained by the above-mentioned personal equation affecting my measures. If we apply this as a systematic correction we get as the probable deviation:

$$\text{H.} - \text{E.H.} = \pm\ 0.032 \text{ tenth-meters,}$$

whence, on the assumption of a probable error of ±0.015 in my wave-lengths, there would follow a probable error of ±0.027 for the wave-lengths of Exner and Haschek. The accuracy is therefore almost the same. This result is not a little surprising, and if it should be confirmed by further comparisons of the tables of Exner and Haschek with measured wave-lengths, it would argue for the adoption of their method of direct reading, at least in cases where the occasional occurrence of isolated larger deviations was not of importance in comparison with the great importance of rapid work.

RELATIONS BETWEEN THE SPECTRUM OF MOLYBDENUM AND THAT OF THE SUN.

As a preliminary result of his comparisons of metallic spectra with the solar spectrum, Rowland published two lists of those metals whose presence in the absorbing stratum of the Sun may be regarded as certain. In these lists the metals are are arranged, first in the order of intensity of the corresponding solar lines, and second, in the order of the number of observed coincidences. In both cases molybdenum occupies a position near the middle. Since in the latter list molybdenum precedes magnesium, for which over twenty coincidences were observed, molybdenum should be represented by at least an equal number of coincidences in the general solar spectrum. But, if we search Rowland's list of solar spectrum wave-lengths for coincidences

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[1] The lines at λ3651.30 and 3782.17, which showed the unusual difference of 0.18 tenth-meters, were excluded in taking the average.

with molybdenum, we find only seven such, whence it must be assumed that Rowland wished to include only the very strongest lines in this list, expressly designated as provisional, and that he considered a further examination of the reality of the coincidences necessary for the less conspicuous lines. This view seems the more probable on account of the fact that with few exceptions the ultimate decision of this question of coincidence is rendered extremely difficult by the very slight intensity of the solar lines concerned in comparison with the molybdenum lines.

The above-mentioned lines of molybdenum occurring in Rowland's list of solar lines are the following:

λ	Intensity in ⊙ (Rowland)	λ	Intensity in ⊙ (Rowland)
3132.75	1	3304.37	1
3170.45	2	3798.40	0
3194.09	000	3864.25	1
3264.53	0		

Only the first two of these lines fall within the limits of my previous observations of the arc-spectrum of molybdenum. They appear on my plates with a very conspicuous intensity, far surpassing all the other lines of the spectrum, and they are greatly broadened and contain narrow, sharp absorption lines which can be observed to coincide beyond a doubt with two fine solar lines. The line at λ 3903.07, which together with the two just-mentioned lines constitutes the most conspicuous element of the whole spectrum, is of almost the same intensity and otherwise of similar appearance. Rowland gives in the solar spectrum at λ 3903.09 a very strong line, ascribed to *Fe* and *Cr*, of which the solar analogue of the *Mo* line, if present, is probably a faint and very close companion not separable from it. The intensity of the solar line given by Rowland in itself makes improbable any relation to the molybdenum line, and this is further confirmed by the fact that on my double exposures to the molybdenum and iron spectra a separation of the two in the sense $\lambda_{Mo} < \lambda_{Fe}$ was suspected on account of the reversal of the two lines. If the *Mo* line in question is represented in the solar spectrum like the two other lines, as can hardly be doubted, then the corresponding solar line must be so closely blended with the line at λ 3903.09 that they could not have been separated by Rowland. We have in this fact without doubt the reason why Rowland left this strong line of molybdenum unmentioned in his list of the solar lines.

I know nothing as to the intensity of the remaining lines attributed by Rowland to *Mo*. With the exception of the last, they are all lacking from Exner and Haschek's list[1] of the stronger lines of the arc-spectrum, while the three principal lines of the arc-spectrum also appear there as the strongest lines of the entire spectrum.

The catalogue of wave-lengths shows that the number of more or less certain coincidences with solar lines which I have been able to observe in this investigation of the *Mo* spectrum, aside from those already mentioned, is very limited. If we consider only those cases in which on account of the greater intensity of the *Mo* lines, the suspicion of contamination by a foreign metal may be regarded as excluded, we obtain the following summary:

λ	*i*		Sun	(Rowland)	
	Mo	⊙	λ	*i*	
3563.30	2.3	1	3563.30	000	
3626.33	2.3	1+	3626.33	1	*Fe*
3664.98	3	1	3664.97	000	
3669.50	2.3	1	3669.54	00	
3969.25	2.3	?	3969.29	0	*Cr, Co*
4084.54	3	?	4084.58	0	
4102.33	2.3	1	4102.32	0	*V*
4185.98	3	1	4185.94	0	
4269.44	2.3	1	4269.45	0	
4277.38	3	?	4277.38	1	
4517.30	3	1.2	4517.32	0	*Co*
4558.30	2.3	1	4558.29	0	
4610.07	3	1	4610.09	0	
4627.70	2.3	1	4627.73	0	
4662.95	3	1	4662.93	0	
4776.54	3	1.2	4776.55	0	*d? Co*
4783.16	2.3	1	4783.17	00	

With the exhibit of this table, in connection with what has been

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[1] *Wien. Sitzungsber.*, 106, 1897.

said above as to the three principal lines of *Mo*, the presence of the metal in the general absorbing layer of the Sun may be regarded as proven. My investigations thus far do not permit a decision as to how far the remaining lines of *Mo* of greater intensity are represented in the general solar spectrum. The following comparison of these strong *Mo* lines with Rowland's solar spectrum indicates with considerable probability that in several cases this is true. In making this comparison I have assumed the possibility of a coincidence only in cases where the difference of wave-lengths does not exceed 0.05 tenth-meters.

Mo		Sun (Rowland)		
λ	*i*	λ	*i*	Remarks
3508.26	2.3	3508.23	000	
21.56	2.3	.....		
37.41	3	37.44	0000	
42.32	2.3	....		
58.25	3	58.21	1	
70.82	2.3	70.83	0000	
3582.03	3.4	3582.08	1	
3603.10	2.3	3603.11	0000	
14.42	3	14.45	0000	
24.60	3	24.60	0000	
29.45	2.3	29.49	000	
38.35	2.3	38.38	1	
57.53	2.3	57.56	1	*Fe*
59.51	3.4	.....		
72.97	3	72.94	0000	
80.75 80.85	3.4	80.80	3	no coinc.
90.72	2.3	90.73	0000	
3695.09	3.4	3695.04	0000	
3727.86	3	3727.83	1	
32.91	3	32.89	2	
42.48	2.3	.....		
70.66	2.3	70.67	000	
3781.75	2.3	3781.75	1	
3802.00	2.3	02.05	00	*Mn*
19.98	2.3	19.94	00	
26.85	2.3	26.84	0	
29.04	3−	.....		
33.92	3	33.92	0	
3869.25	2.3	.....		
3901.95	2.3	.....		
3943.19	3	.....		
4062.24	2.3	4062.20	00	
70.05	3+	70.05	000	
4081.62	3	4081.58	00	
4107.63	3	4107.65	5	*Ce, Fe, Zr*
20.26	3	.....		
43.73	4	.....		

Mo		Sun (Rowland)		
λ	*i*	λ	*i*	Remarks
4149.14	2.3	....		
55.47	2.3	55.48	00	
55.77	2.3	55.80	00	
57.59	2.3	57.59	00	
62.85	2.3	62.83	1	no coinc.
88.49	4	88.48	00	
4194.74	2.3	4194.78	00	
4232.75	3+	4232.76	00	*V*
41.03	2.3	.....		
46.19	2.3	46.18	0	
52.03	2.3	52.04	000	
77.08	3	.....		
88.82	3+	.....		
92.34	3	.....		
93.42	3	.....		
4294.07	3	4294.08	000	
4318.13	2.3	.....		
26.33	3	.....		
50.53	3−	4350.55	00	*Ba?*
69.23	2.3	4369.25	00	
4381.82	4	.....		
4411.76	2.3	4411.75	00	
11.90	3	11.88	00	
23.79	2.3	23.75	000	
26.86	2.3	26.84	000	
42.37	2.3	.....		
57.55	3.4	.....		
68.46	3	68.46	00	
73.37	2.3	73.38	000	
74.78	4	74.74	00	
4485.16	2.3	85.12	000	
4491.46	3	.....		
4506.13 06.22	3	4506.09 06.26	000 00	 *Ba*
12.32	2.3	.....		
24.53	3	24.57	1	*Mn*
29.59	2.3	.....		
37.00	3+	.....		

Mo		Sun (Rowland)			*Mo*		Sun (Rowland)		
λ	*i*	λ	*i*	Remarks	λ	*i*	λ	*i*	Remarks
4576.70	3—	76.69	00		5097.71	2.3	5097.67	0	no coinc.
4595.35	3	4595.39	00		5171.33	3	.....		
4621.57	2.3	.....			73.14	3	.....		
27.70	2.3	4627.73	0		5174.35	3	.....		
62.11	2.3	62.15	1	*Fe?*	5238.41	3	5238.42	000	
62.95	3	62.93	0		5241.09	3	5241.04	000	
72.11	3—	72.09	000		5360.76	4.5	.....		
4688.41	2.3	.....			5364.50	3.4	.....		
4707.44	3.4	4707.46	5	*d? Fe*	5437.97	2.3	5438.00		
08.43	3—	08.46	000		50.73	2.3	.....		
18.13	2.3	.....			5473.64	4	.....		
29.36	2.3	29.38	0000		5506.75	6	5506.72	000	
31.64	3.4	31.65	4	*Fe?*	33.26	6	33.25	000	
50.60	2.3	.....			56.55	2.3	.....		
58.71	2.3	.....			68.88	2.3	68.92	0000	
60.39	4	60.40	0000		5570.69	6	.....		
75.87	2.3	.....			5611.20	3	.....		
85.34	2.3	.....			32.74	4	.....		
4796.75	2.3	.....			35.14	2.3	.....		
4811.28	2.3	4811.24	00	*Ti*	50.40	4	5650.42	0000	
19.47	3	.....			74.77	2.3	.....		
30.73	3	30.71	0000		5678.18	2.3	.....		
4868.23	3	.....			5689.39	4.5	.....		
4904.03	2.3	.....			5705.97	3	.... .		
50.83	2.3	4950.80	0000		22.98	3.4	.....		
57.78	3	?			51.67	4.5	5723.00	0000	
4979.32	2.3	.....			5792.10	4	5792.14	00	
5016.99	2.3	.....			5858.52	4	5858.50	00	
60.07	2.3	5060.11	0000		5888.61	4	5888.65	0000	
80.23	2.3	.....							

A close examination of this table hardly permits a doubt that numerous cases of actual identity occur among these approximately equal wave-lengths. Nevertheless the extraordinary faintness which almost universally characterizes the solar lines here in question renders exceedingly difficult the final decision of the question of coincidence, even with the use of the greatest possible dispersion; while, on the other hand, this faintness gives a sufficient explanation of the fact that these solar lines appear in only the rarest cases on my plates taken hitherto. The beautiful plates which I have recently obtained with the above-mentioned concave grating will, it is hoped, assist in the further solution of this special question.

The great contrast in the intensity of the solar and *Mo* lines, which are to be regarded as belonging to the general solar spectrum, from what has preceded directly suggests the analogous, though less pronounced, relations which I have previously observed in connection with the spectrum of vanadium. In this metal also only the principal lines of the arc-spectrum are represented in the general solar spectrum, but the lines offer considerably less difficulty in observation on account of a less excessive faintness. Since these vanadium lines have a considerable intensity in Sun-spots according to Young's observations, it would be natural to suspect a similar behavior of the molybdenum lines. To my knowledge nothing is known on this point, however, and the decision of the question will necessitate investigations of the spot spectra of much greater completeness than those which are at present available.

THE VARIABLE STAR 7582 *X CEPHEI.*

By J. A. PARKHURST.

THE variability of this star (R. A. $21^{h}\ 3^{m}\ 38^{s}.5$; Dec. + 82° 39′ 50″.3 (1900) was noticed by Madame Ceraski in 1898 from an examination of photographs taken at the Moscow Observatory by M. Blajko).[1] Brief notices in regard to the star have been published in various journals, to which reference will be made later, but so far no report approaching completeness has appeared.

INSTRUMENTS.

The visual and photometric observations were made with a 6-inch (157 mm) Brashear reflector and the 12 (305 mm) and 40-inch (101 cm) refractors of the Yerkes Observatory; the photograph of the field reproduced in Plate I was made with the 24-inch reflector, the original negative having a field three inches square, covering 1° 52′. The central part of this field, enlarged four and one-half diameters, appears in the plate.

The photometric observations were made with the equalizing wedge photometer devised by Professor E. C. Pickering and described in this JOURNAL, **13**, 249;[2] the constant of Wedge II there found, **0.130** magnitude, being used. This value of the constant has been confirmed by Mr. Edward S. King at the Harvard College Observatory.[3] In 1902 a different wedge (V) was used, whose constant proved to be somewhat different from Wedge II. A new determination of the constant of Wedge V, as yet unpublished, was made in the same manner as that of Wedge II, the resulting value, **0.110** magnitude, being used in the reductions.

POSITION OF THE VARIABLE.

The variable was connected with the comparison stars *a* and *b* on October 11, 1898, with the filar micrometer on the 6-inch

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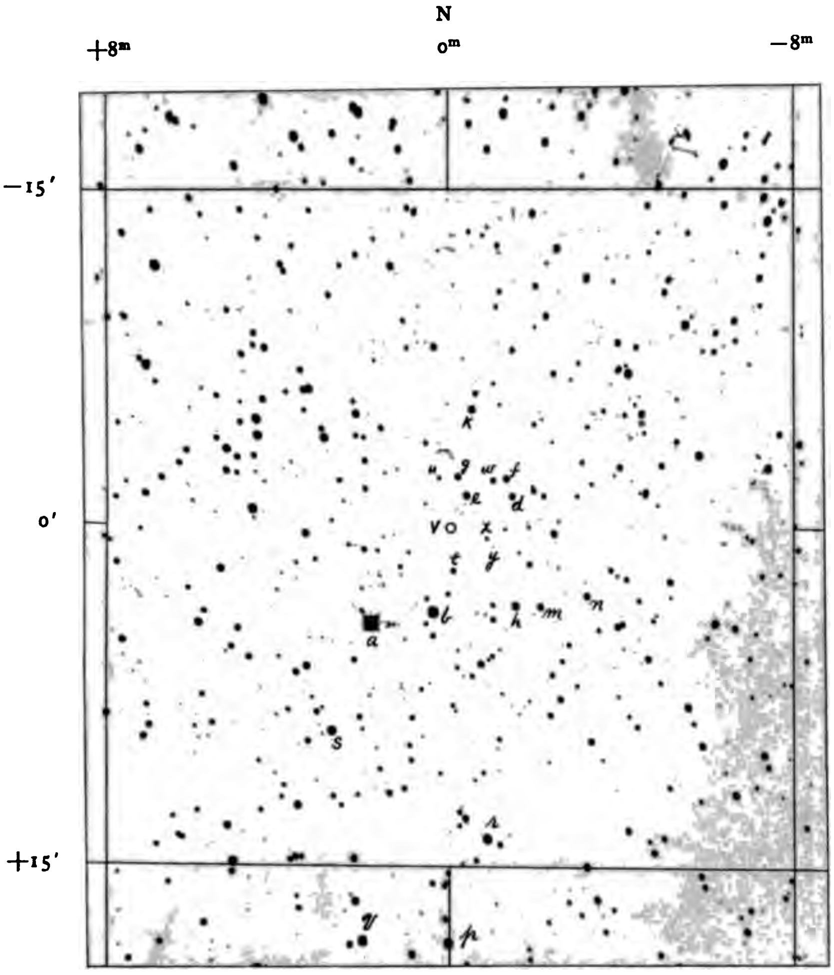
[1] *Astronomische Nachrichten*, **147**, 141.

[2] See sectional drawing, Fig. 1, *loc. cit.*

[3] *H. C. O. Annals*, XLI, 242.

PLATE I.



Scale: 1 mm=20″

7582 *X CEPHEI.*

($21^h\ 3^m\ 38^s.5$; $+82°\ 39'\ 50''$.)

reflector, but, as it was thirteenth magnitude at that time, the position found was not very precise, differing nearly 13″ from the final place. The measures were repeated on October 3, 1899, when the variable had risen to tenth magnitude; with the following results:

b = *Carrington* 3222	21^{h}	06^{m}	$59^{s}.5$	$+82^{\circ}$	$25'$	$05''.7$	(1855)
Precession		—02	57.5		+10	53.2	
b	21	04	02.0	82	35	58.9	(1900)
Δ(*bv*)		—00	23.1		+03	51.4	
v from *b*	21	03	38.9	82	39	50.3	(1900)
a = *Carrington* 3225	21	08	22.7	82	24	28.9	(1855)
Precession		—02	55.0		+10	57.0	
a	21	05	27.7	82	35	25.9	(1900)
Δ (*av*)		—01	49.6		+04	24.3	
v from *a*	21	03	38.1	82	39	50.2	(1900)
v mean	21	03	38.5	82	39	50.3	(1900)
Precession		+03	00.7		—10	52.2	
v	21	06	39.2	82	28	58.1	(1855)

COMPARISON STARS.

When the variable had faded below the limit of the 40-inch refractor I sent a request to Professor Keeler, the late director of the Lick Observatory, to have the field photographed with the Crossley reflector, and he kindly sent me a plate taken July 24, 1900, with an exposure of two hours. The co-ordinates of the comparison stars were measured on this plate by Dr. Caroline E. Furness, with the Repsold measuring machine of Vassar College Observatory, for which courtesy I wish to record in this place my thanks. The results of these measures, with the magnitudes described later, are given in Table I.

The measurement of the light of these comparison stars, one of the principal objects of this investigation, was carried on in the following manner:

Five *Meridian Photometer* stars, lying near the field, were

TABLE I.

Comparison Stars for *7582 X Cephei.*

Letter	Co-ordinates from V		Light		Letter	Co-ordinates from V		Light	
	R. A.	Dec.	Mag.	Steps		R. A.	Dec.	Mag.	Steps
	s	′ ″				s	′ ″		
n	−190	− 3 11	12.68	25.8	*k*	− 30	+ 5 11	12.29	29.0
l	−144	− 0 23	12.79	25.8	*e*	− 23	+ 1 20	12.43	24.4
m	−125	− 3 39	12.0	29.0	*g*	− 10	+ 2 11	12.66	22.9
h	− 91	− 3 35	11.99	29.0	*t*	− 4	− 2 1	14.18	17.8
d	− 87	+ 1 19	12.88	25.8	*p*	+ 1	−18 35	10.2	37.4
f	− 78	+ 2 5	13.23	22.5	*u*	+ 16	+ 2 7	14.88	13.5
w	− 60	+ 2 0	13.98	17.0	*b*	+ 23	− 3 51	9.12	42.3
r	− 51	−13 57	10.08	37.8	*a*	+109	− 4 24	8.24	....
y	− 55	− 0 56	17.0	0.0	*q*	+115	−18 29	10.6	36.5
x	− 50	− 0 36	15.63	7.5	*s*	+160	− 9 11	10.86	32.8

b = *B. D.* + 82°635 = *Carrington* 3222.
a = *B. D.* + 82 636 = *Carrington* 3225.

TABLE II.

Standard Magnitude Stars from *Harvard Annals*, XXIV.

Letter	*B. D.*		1855		H. C. O.
	No.	Mag.	R. A.	Dec.	Mag.
			h. m.	° ′	
A	+82°648	8.0	21 30.2	+82 21	7.99
B	+81 737	7.5	21 25.2	+81 54	7.83
C	+81 736	7.9	21 24.7	+81 24	7.47
D	+81 735	7.8	21 23.5	+81 8	7.73
E	+81 742	8.0	21 32.4	+81 6	8.07

selected from *Harvard Annals*, XXIV; their notation, positions, and photometric magnitudes being given in Table II. With these stars as standards, the magnitude of four comparison stars between eighth and eleventh magnitudes, *a*, *b*, *s*, and *r*, were measured with the photometer attached to the 6-inch reflector. From these as standards, four stars between the eleventh and thirteenth magnitudes were measured with the 12-inch; and finally the remaining stars were measured with the 40-inch. That the reader may be able to form an independent estimate of the merits of the methods and instruments for this work, the measures are given in detail in Table III, which is nearly self-explanatory.

There are three main dangers to be guarded against in this work: (1) the lack of close resemblance between the real and artificial stars; (2) variation in the light of the artificial star; and (3) variation in the transparency of the atmosphere, from changing zenith distance or other causes. To insure resemblance in the star images the movable diaphragm close to the lamp was provided with five holes, 0.10, 0.15, 0.20, 0.25, and 0.30 mm in diameter, the choice of the hole used being governed by the telescope and atmospheric conditions of each evening. To eliminate the effect of variation in the light of either star, the series of scale readings was repeated in inverse order (given under "Second" in Table III). An inspection of the scale readings and their means will therefore show any variations, either irregular or progressive, in the light of either star, and the final means will tend to eliminate their effects.

In each division of Table III the stars used as standards are given first, with their magnitudes in bold-faced type. The magnitudes sought for the remaining stars were deduced in the following manner: Means were formed of the scale readings (d_0) and magnitudes (M_0) of all the standards. The difference between the mean scale reading for each star and d ($d-d_0$), was converted into magnitudes by multiplication into the wedge constant, and its value (ΔM) added to M_0.

An idea of the errors in the settings and the maximum effect of irregular changes in the light of the stars can be gained from the average deviations of the separate settings from the means. The values are:

For the 6-inch - - - -	0.06 mag.
For the 12-inch - - - -	0.09 mag.
For the 40-inch - - - -	0.10 mag.

The agreement of the final magnitude results is as follows:

Average Deviation of One Night's Measure from Mean

6-inch - - - -	0.10 mag.	4 stars
12-inch - - - -	0.04 mag.	4 stars
40-inch - - - -	0.08 mag.	7 stars

TABLE III.

Photometric Measures of Comparison Stars.

1900, October 19; 6-inch. **Wedge II; seeing very good.**

STAR	SCALE READINGS						MEAN SCALE READING	MAG.
	First			Second				
A	16.5	16.4	17.2	18.1	19.1	18.0	17.55	**7.99**
B	15.4	15.1	15.8	16.2	16.8	14.7	15.67	**7.83**
C	12.0	11.0	11.2	12.5	12.6	11.6	11.82	**7.47**
D	14.2	13.3	14.6	13.4	13.5	12.9	13.65	**7.73**
E	18.0	17.5	17.2	14.9	16.1	15.0	16.45	**8.07**
a	17.9	18.8	16.9	17.4	17.4	17.9	17.72	8.24
b	24.0	23.9	22.9	23.2	24.0	23.1	23.52	9.12
s	36.4	36.9	38.4	38.9	37.1	38.8	37.85	10.86
r	34.2	33.4	33.2	32.0	32.0	30.8	32.60	10.08
p	32.4	34.5	33.8				33.57	10.02
q	37.0	35.9	37.2				36.70	10.6
h	44.0	46.3	44.9				45.07	12.0

1900, November 2; 6-inch. **Wedge II; Moonlight.**

E	16.0	16.0	15.8	16.1	16.8	15.2	15.82	**8.07**
D	12.7	13.0	12.3	13.9	13.2	14.6	13.29	**7.73**
C	11.0	11.7	11.4	11.0	11.6	10.4	11.19	**7.47**
B	15.5	16.2	15.8	15.4	16.1	16.0	15.83	**7.83**
A	16.7	17.4	17.4	17.9	17.4	17.0	17.30	**7.99**
a	18.4	18.9	18.2	18.1	18.8	18.2	18.44	8.31
b	25.8	26.3	24.8	25.8	26.0	24.4	25.52	9.23
s	38.3	38.1	38.2	36.8	37.3	36.2	37.49	10.78
r	34.3	32.9	33.9	33.7	32.6	32.0	33.24	10.23

1900, December 12; 6-inch. Wedge II.

E	19.8	20.8	20.8	20.7	20.8	20.0	20.49	**8.07**
D	18.8	19.4	18.3	16.9	16.8	16.2	17.73	**7.73**
C	16.5	17.6	17.1	15.7	16.1	15.8	16.45	**7.47**
B	19.4	20.3	20.0	18.0	18.6	17.0	18.87	**7.83**
A	21.9	21.0	21.2	20.8	20.1	20.6	20.94	**7.99**
b	29.9	29.8	29.0	28.8	31.0	29.8	29.72	9.22
a	22.8	22.0	22.4	22.5	20.8	22.1	22.10	8.24
h	51.2	53.8	52.4	54.4	53.5	52.7	53.00	12.2
r	35.2	36.0	36.0	35.1	34.0	34.0	35.05	9.92
s	42.7	44.2	43.0	44.4	43.8	42.2	43.39	11.00

TABLE III.—*Continued.*

RESULTING MAGNITUDES FROM MEASURES WITH 6-INCH.

Star	Oct. 19	Nov. 2	Dec. 12	Mean
a	8.17	8.31	8.24	8.24
b	8.92	9.23	9.22	9.12
s	10.79	10.78	11.00	10.86
r	10.10	10.23	9.92	10.08
p	10.23		.....	10.2
q	10.64		.....	10.6

1900, Sept. 12; 12-inch. Wedge II; moonlight, clear.

STAR	SCALE READINGS						MEAN SCALE READING	MAG.
	First			Second				
a	12.7	13.2	13.2	13.5	13.1	13.1	13.13	**8.24**
b	20.5	20.0	20.6	21.6	20.9	20.8	20.74	**9.12**
h	45.0	41.5	43.9	40.3	42.0	43.1	42.30	11.98
n	51.1	46.5	48.6	47.4	47.9	46.4	47.98	12.71
l	49.0	51.8	48.8	48.2	49.3	47.0	49.02	12.84
d	47.2	49.6	48.0	48.2	49.9	49.9	48.90	12.84

1900, October 25; 12 inch. Wedge II; seeing good.

a	12.5	12.9	13.7	13.0	13.0	11.9	12.83	**8.24**
b	20.9	21.0	20.9	21.1	20.9	21.0	21.61	**9.12**
s	29.2	30.1	30.0	30.0	30.9	29.9	30.22	**10.86**
d	49.0	48.7	48.3	48.0	47.0	47.5	48.09	12.92
h	41.3	42.3	41.0	41.2	42.1	40.8	41.45	12.00
n	45.0	47.8	47.7	47.4	46.5	44.1	46.42	12.64
l	46.1	46.1	44.2	49.0 49.1	47.0 49.5	45.0 50.8	47.09	12.73

RESULTING MAGNITUDES FROM MEASURES WITH 12-INCH.

Star	Sept. 12	Oct. 25	Mean
h	11.98	12.00	11.99
d	12.84	12.92	12.88
l	12.84	12.73	12.79
n	12.71	12.64	12.68

TABLE III.—*Continued.*

1900, September 13; 40-inch. Wedge II; seeing good.

Star	Scale Readings						Mean Scale Reading	Mag.
	First			Second				
s	14.2	18.2	15.9	16.9	15.1	14.1	15.74	10.86
h	22.4	22.2	22.8	22.2	23.3	22.0	22.49	11.99
d	25.8	28.1	26.8	....	....	....	26.90	12.88
l	29.8	27.2	29.2	28.5	27.0	30.0	28.62	12.79
t	38.8	40.8	38.8	37.0	37.4	36.9	38.29	14.06
x	49.3	49.3	47.1	49.3	49.4	50.0	49.07	15.47
f	31.1	29.9	32.1	....	....	....	31.10	13.13
w	36.2	37.2	36.2	....	....	....	36.53	13.82
e	26.1	26.2	26.0	25.9	24.0	27.5	25.95	12.46
g	26.5	29.5	27.2				27.73	12.69
u	43.8	43.3	44.4				43.83	14.78
k	26.7	22.8	24.6				24.70	12.29

1902, January 7; 40-inch. Wedge V; seeing good.

d	21.9	25.7	24.7	24.8	23.6	24.7	25.4	24.1	24.42	12.88
l	29.2	27.9	29.9	28.2	22.5	23.5	21.8	21.8	25.60	12.79
n	22.2	24.0	21.7	23.2	20.4	20.4	18.8	19.3	21.18	12.68
e	17.0	20.3	20.4	20.9	22.0	19.7	21.8	20.1	20.15	12.39
x	49.8	51.7	48.8	50.7	51.1	52.8	52.0	50.6	50.94	15.77
g	20.0	23.8	21.8	23.2	23.2	22.5	21.8	21.8	22.27	12.62
w	38.1	39.2	38.6	38.2	32.9	33.1	33.8	33.3	35.91	14.12
f	28.7	29.5	30.6	28.9	28.2	28.8	28.0	26.2	28.62	13.32
t	33.2	35.0	33.7	36.0	37.2	37.2	37.4	37.8	35.94	14.12
u	42.9	44.3	42.7	43.7	43.5	43.4	44.2	43.8	43.57	14.96

RESULTING MAGNITUDES FROM FIRST TWO SETS WITH 40-INCH.

Star	Sept. 13	Jan. 7	Mean
e	12.46	12.39	12.43
k	12.29	.....	12.29
g	12.69	12.62	12.66
f	13.13	13.32	13.23

TABLE III.—*Continued.*

1900, September 6; 40-inch Wedge II; bright Moon.

Star	**Scale Readings**						**Mean Scale Reading**	**Mag.**
	First			**Second**				
d	22.0	21.5	23.0	29.4	27.8	25.1	24.80	12.88
l	28.2	29.5	29.2	33.0	30.5	29.9	30.05	12.79
e	25.4	24.8	27.0	25.4	25.0	23.6	26.20	12.43
g	27.8	28.0	28.1	26.3	30.3	27.0	27.92	12.66
f	30.6	31.8	32.8	30.0	32.7	33.0	31.82	13.23
w	38.0	35.9	35.3	36.8	39.0	39.0	37.34	13.99
t	38.7	40.8	40.6	....	....	....	40.05	13.35
u	41.9	44.2	43.1	46.8	45.0	45.5	44.42	14.91

1900, May 8; 40-inch. Wedge II; seeing poor.

e	28.8	31.2	28.2	27.2	30.4	27.7	28.5	31.8	29.23	12.43
g	27.8	27.6	31.2	28.5	32.2	31.8	33.2	26.5	29.86	12.66
t	42.2	41.8							42.0	14.2
u	48.9	48.9							48.9	15.1

RESULTING MAGNITUDES FOR *t*, *u*, and *w* WITH 40-INCH.

Star	Sept. 13	Jan. 7	Sept. 6	May 8	Mean
t	14.06	14.12	14.35	(14.2)	14.18
u	14.78	14.96	14.91	(15.1)	14.88
w	13.82	14.12	13.99	......	13.98

1902, May 29; 40-inch. Wedge V; seeing fairly good.

Star	**Scale Readings**								**Mean Scale Reading**	**Mag.**
	First				**Second**					
t	39.0	39.2	38.4	39.8	39.5	39.4	40.1	39.0	39.30	14.18
u	44.7	45.4	45.6	45.8	45.0	45.0	46.0	45.5	45.38	14.88
x	52.4	52.6	52.5	54.0	52.2	50.5	52.0	53.5	52.47	15.66

RESULTS FOR ALL MEASURES OF *x* WITH 40 INCH.

Star	Sept 13	Jan. 7	May 29	Mean
x	15.47	15.77	15.66	15.63

MAGNITUDE CURVE.

The visual observations of the variable were made by Argelander's method, and a light-scale formed from the resulting intervals between the comparison stars, expressed in steps. Fig. I shows the correspondence between the light of the stars expressed in steps and the magnitude found by the photometer.

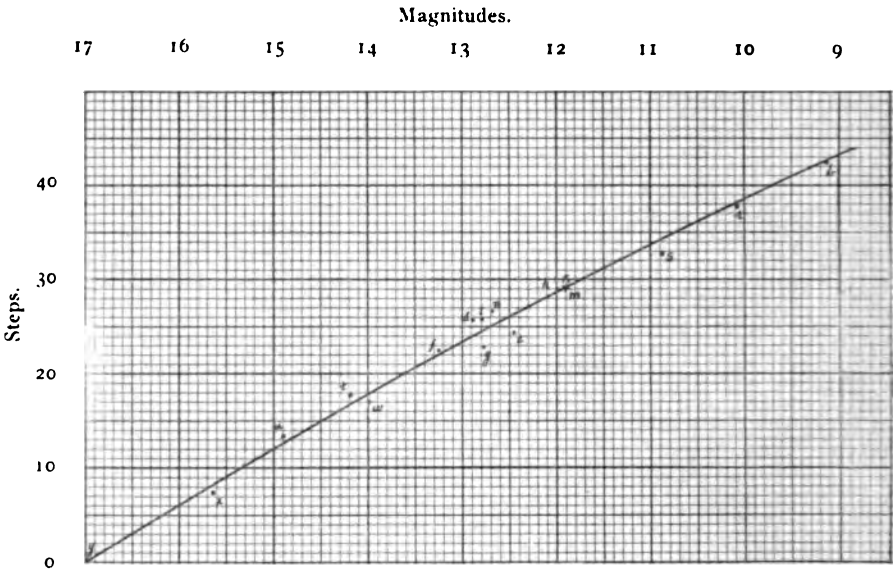


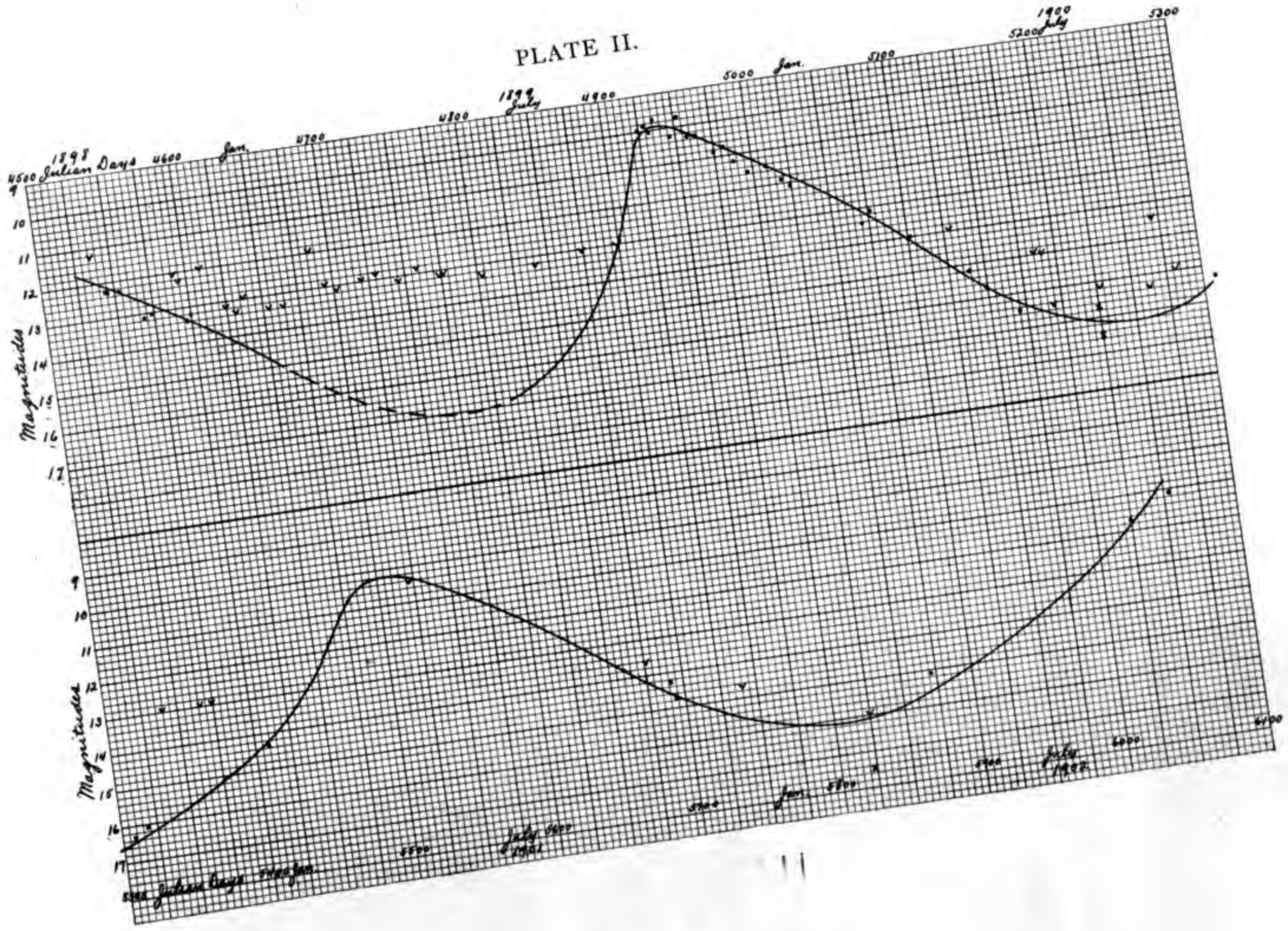
FIG. I.—Magnitude Curve of *X Cephei.*

It is platted with the photometric magnitudes as abscissæ and the step values in the light-scale as ordinates. The average distance between the platted points and the smooth curve drawn through them is about 0.10 magnitude. This curve serves to fix the magnitudes of the three stars, *y*, *k*, and *m*, which were not measured with the photometer, and also to translate the brightness of the variable, expressed in steps in the comparisons, into magnitudes.

VISUAL OBSERVATIONS OF THE VARIABLE.

These observations are given in detail in Table IV, the headings of the columns leaving little explanation necessary. In the

PLATE II.



Light Curve of *X Cephei*.

TABLE IV.

7582 X Cephei

Comparisons of the Variable by Argelander's Method.

No.	Date				Ocular	Aperture	Comparisons
	Month	Day	Hour	Julian Day			
	1898		C. S. T.	G. M. T.			
1	Sept.	3	9	4536.6	80	6	*a* and *b* seen, nothing else near
2		6	9	4539.6	150	6	*v* 1-2 *d*, *d* 2 *e*, *e* 1 *f*, *e* 1 *g*
3		7	9	4540.6		6	No change
4		20	8	4553.6	150	6	*h* 2 *v*. *v* limit, is this *v?*
5	Oct.	5	8	4568.6	150	6	*e* 2 *v*, *e* 1 *g*, *e d*, *d* 3 *f*
6		11	8	4574.6	80	6	*g* 1 *v*, *e* 1-2 *v*, *d* 2 *v*, *v* 2 *f*
7		28	6	4591.5	150	6	*v*, *d*, *f*, *e* and *g* not seen
8		31	6	4594.5	80	6	*v*, *d*, *f*, *e* and *g* not held
9	Nov.	2	7	4596.5	200	6	*e* 3 *v*, *g* 1-2 *v*, *f* 1-2 *v*
10		6	7	4600.5	80	6	*e*, *g* and *d* seen, *f and v* glimpsed
11		16	7	4610.5	200	6	Nothing seen near *v*
12		30	6	4624.5	150	6	*e*, *d*, *f* and *g* seen, *v* not seen
13	Dec.	7	7	4631.5	200	6	*v* not seen
14		13	6	4637.5	150	6	*v* not seen
15		30	6	4654.5	200	6	*d*, *e*, *f* and *g* seen, *v* not seen
	1899						
16	Jan.	8	6	4663.5	200	6	*d*, *e*, *f* and *g* seen, *v* not seen
17	Feb.	1	6	4686.5		6	*d*, *e*, *f*, *g* and *v* not seen
18		7	7	4692.5		6	*d*, *e* and *g* seen, *v* not seen
19		15	18	4702.0	200	6	*d*, *e*, *f* and *g* seen, *v* not seen
20	Mar.	6	7	4720.5	150	6	*d*, *e*, *f* and *g* seen, *v* not seen
21		15	8	4729.5		6	*e* seen, *v* not seen
22		31	8	4745.5	150	6	*d*, *e*, *f* and *g* seen, *v* suspected
23	Apr.	12	8	4757.6	150	6	*e* and *d* seen, *v* not seen
24		28	9	4773.6	200	6	*d*, *e*, *f* and *g* seen, *v* not seen
25	May	1	9	4775.6	200	6	*d*, *e*, *f* and *g* well seen, *v* not seen
26		29	9	4804.6	200	6	*d*, *e*, *f* and *g* well seen, *v* not seen
27	July	6	10	4842.7	150	6	*d*, *e*, *f* and *g* well seen, *v* not seen
28	Aug.	5	9	4872.6	150	6	*d*, *e*, *f* and *g* seen, *v* not seen
29		30	9	4897.6	150	6	*d*, *e* and *g* seen, *v* not seen
30	Sept.	26	7	4924.5	150	6	*b* 4 *v*, *v* 0-1 *r*, *v* 1-2 *p*
31		30	7	4928.5	150	6	*b* 2-3 *v*, *v* 1-2 *r*, *v* 1 *p*
32	Oct.	3	8	4931.6	80	6	*b* 3-4 *v*, *v r*
33		6	7	4934.5	40	6	*b* 2-3 *v*, *v* 2 *r*
					150	6	*b* 3-4 *v*, *v* 2-3 *r*
34		18	7	4946.5	80	6	*b* 4 *v*, *r* 1 *v*, *v p*, *v* 1 *q*
35		24	7	4952.5	40	6	*b* 3-4 *v*, *v* 2-3 *r*, *v* 2-3 *p*
36		29	7	4957.5	150	6	*b* 4-5 *v*, *r* 2-3 *v*
					40	6	*b* 4 *v*, *r* 1 *v*, *v* 4 *s*
37	Nov.	4	7	4963.5	150	6	*b* 5 *v*, *v* 3 *s*
					40	6	*b* 4-5 *v*, *v r*, *v* 3 *s*
38		15	7	4974.5	150	6	*b* 10 *v* ±, *r* 2 *v*, *v* 2 *s*
39		22	7	4981.5	40	6	*b* 6-8 *v*, *r* 3 *v*, *v* 2 *s*
40		28	7	4987.5	150	6	*r* 4 *v*, *s* 1 *v*, *v* 4 *h*
41	Dec.	6	7	4995.5	150	6	*s* 2 *v*, *v* 2 *h*
42		19	6	5008.5	150	6	*s v*, *v* 1-2 *h*

TABLE IV.

7582 X Cephei

Reductions of Observations.

	Details in Steps	**Means**		**Seeing**	**Remarks**
		Steps	**Mag.**		
1		<27	<11.3	moon	limit 10<*b*
2	27.3	27.3	12.27	fair	limit *g*
3			12.3±		
4	27.0	27.0	12.30	fair	limit *v*, is it *v*?
5	22.4	22.4	13.16	good	
6	21.9, 22.9, 23.8, 24.5	23.2	13.01	good	limit *f*
7		<28	<12.1	full moon	limit 1<*h*
8		<27	<12.3	fair	limit 2<*h*
9	21.4, 21.4, 21.0	21.2	13.40	good	
10		22±	13.2±	good	
11		<29	<12	fair	limit *h*
12		<22	<13.2	good	limit *f* = 3 < *e*
13		<21	<13.4	good	limit 1 < *f*
14		<23	<13.0	fair	limit *g*
15		<21	<13.4	good	limit 1 < *f*
16		<21	<13.4	good	limit 1 < *f*
17		<29	<12	poor	limit *h*
18		<23	<13.0		
19		<22	<13.2	good	
20		<23	<13.0		
21		<24	<12.9	clouds	
22		<22	<13.2	good	
23		<24	<12.9	good	
24		<22	<13.2	good	
25		<22	<13.2	good	
26		<22	<13.4	good	
27		<22	<13.3	good	
28		<23	<13.1		
29		<23	<13.1	fair	
30	38.3, 38.3, 38.9	38.5	10.00	good	
31	39.8, 39.3, 38.4	39.1	9.88	good	
32	38.8, 37.8	38.3	10.05	good	
33	39.8, 39.8 38.8, 40.3	39.9	9.74	fair to good	
34	38.3, 36.8, 37.4, 37.5	37.5	10.22	moon, fair	
35	38.8, 40.3, 39.9	39.7	9.76	good	
36	37.8, 34.8 38.3, 36.8, 36.8	36.9	10.33	good	
37	37.3, 35.8 37.8, 37.8, 35.8	36.9	10.33	good	
38	32.3, 35.8, 34.8	34.2	10.87	moon, fair	
39	35.3, 34.8, 34.8	34.9	10.78	fair to good	
40	33.8, 31.8, 33.0	32.8	11.20	fair to good	
41	30.8, 31.0	30.9	11.57	fair	
42	32.8, 30.5	31.6	11.44	fair	

TABLE IV—*Continued.*

No.	Date				Ocular	Aperture	Comparisons
	Month	Day	Hour	Julian Day			
	1899		C. S. T.	G. M. T.			
43		29	7	5018.5	150	6	*s* 3 *v*, *h* 1 *v*, *v* 4 *l*
	1900						
44	Jan.	4	7	5024.5	150	6	*s* 4-5 *v*, *h* 2 *v*, *v* 3 *l*
45		21	6	5041.5	350	40	
46	Feb.	18	14	5069.8	350	40	*e* 8 *v*, *v* 8 *t*, *v* 2 *e*
47		25	9	5076.6	275	12	*e* 1 *v*, *v f*, *v* 3 *t*
48	Mar.	21	8	5100.6	275	12	*t* 1 *v*, *v* 1 *w*
49		22	10	5101.7	350	40	*v t*, *v* 1 *w*
50	Apr.	18	13	5128.8	350	40	*v* not seen, *t* glimpsed
51		27	12	5137.8	237	40	*w* 6 *v*, *t* 6 *v*, *u* 3 *v*, *v* 3 *x*
52	May	8	14	5148.8	350	40	*u* 5 *v*
					460	40	*u* 6 *v*, *x* 0-1 *v*
					460	40	*u* 5 *v*, *x* 1 *v*, *w* 8 *v*, repeated
53		29	13	5169.8	237	40	*x* 4-5 *v*
54	June	13	12	5184.8	350	40	*v*, *u* or *x* not seen, *w* seen
55		19	14	5190.8	350	40	*v* and *x* not held
56		21	12	5193.0	237	40	*v* not seen
57	July	24		5225			
58		25	15	5226.9	460	40	*v* not seen
59	Aug.	29	15	5261.9	460	40	*v* not seen
60	Sept.	6	9	5269.6	237	40	*v* or *x* not seen
61		13	8	5276.6	237	40	*v* not seen
62	Oct.	16	9	5309.6	460	40	*x* 3 4 *v*, *v* 4 *y*
63		25	11	5318.7	460	40	*x* 2 *v*
64	Nov.	15	6	5339.5	150	6	*v* not seen
65	Dec.	11	6	5365.5	150	6	*v* not seen
66		19	6	5373.5	150	6	*v* not seen
	1901						
67	Jan.	24	7	5409.5	350	40	*t* 2 *v*, *v* 2 *u*
68	May	16	8	5521.6	80	12	*b* 5 *v*, *r* 2 *v*, *v* 4 *s*
69	Oct.	18	8	5676.6	80	12	*v* not seen
70	Nov.	1	8	5690.6	275	12	*t* 2 *v*, *v* 1 *w*, *v* 1 *u*
71		4	9	5693.6	460	40	*t* 4 *v*, *w* 4 *v*, *v u*
72	Dec.	21	7	5740.5	350	40	*v* not seen
	1902						
73	Mar.	13	11	5827.0			24-inch reflector, *v* ½^{m} ± < *y*
74		15	14	5824.9	460	40	*v* or *y* not seen
75	May	2		5872	237	40	*t* 6 *v*, *u* 4 *v*, *v* 4 *x*
76		29	9	5899.6	237	40	photometer
77	Oct.	1	9	6024.6	237	40	*s* 2-3 *v*, *b* 10 *v*, *v* 10 *h* ±
78		31	9	6053.6	237	40	*s v* ±

TABLE IV — *Continued*

	Details in Steps	Means		Seeing	Remarks
		Steps	Mag.		
43	29.8, 28.0, 29.8	29.2	11.89	good	
44	28.3, 27.0, 28.8	28.0	12.11	fair	
45				good	Nothing as bright as 16*m* within 1′.5 of *v*
46	16.4, 25.8, 20.9	21.0	13.42	fair, moon	
47	23.4, 22.5, 20.8	22.8	13.11	good	limit t
48	16.8, 18.0	17.4	14.05	good	limit w
49	17.8, 18.0	17.9	14.00	good	
50		<18	<14.0	moon, haze	
51	11.1, 11.8, 10.5, 10.5	10.9	15.20	good	limit, 2-3 $<x$
52	8.5, 7.5, 7.0 7.5, 7.0, 9.0 8.5, 6.5, 9.0	7.8	15.71	fair	limit v
53	3.0	3.0	16.50	fair	limit v
54			<15	moon	limit $1<t$
55			<15	fair	limit $1<t$
56		< 3.0	<16.5		limit $4-5<x$
57			<16.5		Crossley plate
58		< 4.5	<16.2	good	limit $3<x$
59		< 3.5	<16.4	good	limit $4<x$
60		<13.5	<14.7	moon	limit u
61			<16		limit ½ $m<x$
62	4.0, 4.0	4.0	16.33		limit y
63	5.5	5.5	16.09	thro' clouds	
64		<22	<13	good	
65		<22	<13	good	
66		<23	<13	good	
67	15.8, 15.5	15.6	14.39	fair	
68	37.3, 35.8, 36.8	36.6	10.42	good	
69		<19.4	<13.7	fair	limit $3-4<g$
70	15.8, 18.0, 14.5	16.1	14.30	good	limit $1<w$
71	13.8, 13.0, 13.5	13.4	14.76	poor	limit $1<u$
72		<13.5	<14.7	fair, moon	limit u
73			17½ ±	good	
74		< 5	<16	unsteady	limit $2-3<x$
75	11.8, 9.5, 11.5	11.3	15.10	good	
76			15.21	fairly good	
77	30.3, 32.3, 39.0	30	11.7 ±	poor	
78		33	11.1 ±	poor	

used in this work. If we assume 13.0 magnitude as the limit of 6 inches aperture, we have the following table:

Aperture		6	12	40
Magnifying power		200	275	460
		M	M	M
Limit	Observed	13.2	14.2	17.0
	Calculated	13.0	14.5	17.

The visibility of stars fainter than the theoretical limit of a 6-inch reflector seems due to the use of a (proportionally) high power, while the lack in the 12-inch seems due to the comparatively low power.

I wish in this place to acknowledge my indebtedness for assistance in the work to Miss Kate Bloodgood, who has formed the light-scale and reduced the visual observations; to Mr. Ferdinand Ellerman for preparing the photograph of the field for the engraver, and to Mr. Frank Sullivan, who recorded the photometric measures with the 40-inch.

YERKES OBSERVATORY,
December 1902.

THE PROPER MOTIONS OF THE STARS.

By Gavin J. Burns.

Of all methods of investigating the problem of the constitution of the stellar universe, none is more promising than the study of the proper motions of the stars. Some of the inferences that may be drawn from what is already known of the proper motions of the stars will be considered in this paper.

The material for this investigation has been obtained from the catalogue of the proper motions of 2,641 stars by M. J. Bossert, published in the *Annales de l'observatoire de Paris* in 1896. This catalogue is confined to proper motions of over $0^s.01$ in R.A. or $0''.1$ in declination which have been deduced from observations extending over at least fifty years. The following table gives a summary of the stars contained in this catalogue, arranged according to magnitudes. The numbers in the first column are proper motions measured on the arc of a great circle:

Proper Motion	Magnitude									Total
	1 to 1.9	2 to 2.9	3 to 3.9	4 to 4.9	5 to 5.9	6 to 6.9	7 to 7.9	8 to 8.9	9 and over	
Sec. per annum	No.	No.	No.	No.	No.	No.	No.	No.	No.	
0.1 to 0.2	4	10	33	68	128	218	265	236	70	1,032
0.2 to 0.4	4	12	23	50	91	213	271	292	67	1,023
0.4 to 0.8	3	7	9	22	24	64	88	113	24	354
Over 0.8	4	0	8	11	17	30	30	29	14	143
Total	15	29	73	151	260	525	654	670	175	2,552

On examining the above table it will be found that little connection can be traced between the magnitude of a star and its proper motion. The first two lines, for instance, consist of a nearly equal number of stars distributed throughout the various magnitudes in nearly the same proportion. The numbers [illegible] same distribution of proper [illegible] that

[illegible]

[illegible]

[illegible]

[illegible]

[illegible] now generally admitted by astronomers that [illegible] proper motion [illegible] is on an average proportional to [illegible] that a very large proportion of the [illegible] 2,552 stars enumerated must be at nearly [illegible] brighter stars. Each number, in fact, [illegible] represents a group of stars at nearly the same [illegible] we leave out of consideration [illegible] magnitude and over, it will be seen that [illegible] with only three [illegible]. Hence, if we agree to measure the "size" of a star [illegible] it follows that, so far as the stars [illegible] are concerned, they become more numerous as they decrease in size. The apparent exception in the case of stars of the [illegible] magnitude is doubtless due to lack of material for calculating the proper motion of the fainter stars.

The question here arises as to how far the 2,552 stars under consideration may be taken as representative of the stars in general. Now, it is much more likely that, for any given proper motion and for any two given magnitudes, the number of stars of the fainter magnitude will hereafter be augmented by further observation and research than the number of stars of the brighter magnitude. Taking this into consideration, it appears very probable that the stars do, in fact, increase in number as they decrease in size. Doubtless, there is some particular "size" of star which is more numerous than any other, larger or smaller, but there are no data for determining what it is.

Let us next see what light may be gained on the question of the distribution of stars in space.

The following list shows the number of stars under the seventh magnitude

Under magnitude 2.00 there are 40 stars.
From 2.00 to 2.99 there are 99 stars = 2.5×40.
From 3.00 to 3.99 there are 317 stars = 3.2×99.
From 4.00 to 4.99 there are 1,020 stars = 3.2×317.
From 5.00 to 5.99 there are 2,865 stars = 2.8×1,010.
From 6.00 to 6.99 there are 9,554 stars = 3.4×2,865.

The above numbers, except the last, have been obtained by actual enumeration from the Harvard *Photometries*. The 9,554 stars is an estimate made by Mr. J. E. Gore from the numbers in the Harvard *Photometric Durchmusterung*. Professor Newcomb calls the ratio of the numbers of stars of two successive magnitudes (given above) the "star-ratio." It will be noted that the star-ratio to the seventh magnitude has an average value of 3.

Now, suppose that at the distance x_1 there are n stars of such a size as to appear as stars of the first magnitude; that at the distance x_2 a star of the same size appears as a star of the *second* magnitude, and so on. Suppose, further, that the number of stars at the distance x_1 of the second magnitude is $n m_2$, of the third magnitude $n m_3$, etc. Then, on the hypothesis that stars of all sizes are distributed in the ratio 1, r, r^2, r^3 . . . . at the distances x_1, x_2, x_3, x_4 . . . . . , we find that, if stars nearer than x_1 are neglected,

The number of stars of first magnitude $= n$
The number of stars of second magnitude $= nm_2 + nr$
The number of stars of third magnitude $= nm_3 + nm_2r + nr^2$
The number of stars of fourth magnitude $= nm_4 + nm_3r + nm_2r^2 + nr^3$.

Consequently, if R_1, R_2, R_3 are the star ratios,

$$R_1 = m_2 + r$$

$$R_2 = \frac{m_3}{m_2 + r} + r$$

$$R_3 = \frac{m_4}{m_3 + m_2r + r^2} + r \ .$$

We see from the above formulæ that r is always less than the star-ratio, unless $m = 0$, in which case $R = r$. If all the m's be equal, the star-ratio will constantly diminish for higher magnitude. If, as appears to be the case in reality, the m's increase with the magnitude, r might be much less than the star-ratio. Now, it can be readily shown that for a uniform distribution of the stars in space $r = 4$. But $R = 3$. Consequently $r < 3$, and probably r is considerably less than 3. This implies that the stars thin out as their distance from us increases. It is true that this reasoning is not demonstrative, for we have assumed r to be constant. Nevertheless it is difficult to avoid the conclusion that with a star-ratio of 3 the stars do in reality thin out as they recede from our system.

The truth of this may be shown in another way. If the stars were all moving at the same average velocity at right angles to the line of sight, the number of stars having angular proper motions lying between a and $2a$ would be eight times the number of those having proper motions between $2a$ and $4a$, upon the hypothesis of uniform distribution. A glance at the table already given will show how greatly the smaller proper motions fall short of the number we should expect. It is true that this defect of small proper motions may be largely due to insufficiency of data, as large proper motions are much more likely to be discovered than small ones. If this were the only cause, we should expect that, as our knowledge extended, the known number of small proper motions would show a relative increase. But this does not seem to be the case. The following table gives the number of stars in Dunkin's list[1] published in 1863 and Bossert's catalogue published in 1896:

PROPER MOTION IN SECONDS PER ANNUM.	DUNKIN		BOSSERT	
	No. of stars	Per cent.	No. of stars	Per cent.
0.1 to 0.2	222	60	1,032	40
0.2 to 0.4	99	27	1,023	40
0.4 to 0.8	36	10	354	14
Over 0.8	12	3	143	6
Total	309	100	2,552	100

It will be remembered that Bossert's catalogue omits proper motions under $0^{s}.01$ in R. A. Consequently it is deficient in proper motions between $0''.1$ and $0''.2$ of arc. When allowance is made for this deficiency, the two lists will be found to contain nearly the same proportion of proper motions of different mag-

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[1] *Memoirs of R. A. S.*, 32.

nitudes, except for those over 0″.8, in which there is a decided increase. This is exactly the opposite of what might have been anticipated. The inference is that there is in reality a much greater number of stars with large proper motions than there would be if they were uniformly distributed throughout the stellar universe.

Upon the whole we appear to be justified in coming to the following conclusions:

1. The stars increase in number as they decrease in size. In other words, smaller stars are more numerous than larger ones.

2. The stars thin out as their distance from the solar system increases.

Another remarkable fact connected with the distribution of proper motions is that double stars have frequently large proper motions. The following comparison illustrates this:

Average p. m. of 778 stars from first to fifth magnitude (average magnitude = 4) contained in Dunkin's list, 0″.15.

Average p. m. of 54 double stars from first to seventh magnitude (average magnitude = 4.5) from Struve's catalogue, 0″.37.

The following table exemplifies the peculiarity still further:

Magnitude	Average p. m. according to Auwers	Average p. m. according to Kapteyn	Average p. m. of southern double stars (Innes)		Average p. m. of Burnham's double stars	
1	0″.263	0″.196	(7)	0″.71	(3)	0″.07
2	.137		(11)	.09	(6)	.05
3	.096		(26)	.18	(12)	.18
4	.075	.147	(44)	.22	(23)	.07
5	.063	.101	(69)	.18	(58)	.08
6	.055	.079	(39)	.12	(71)	.15
7	.049	.066	(24)	.23	(15)	.12
8	.045	....	(12)	.37	(18)	.21

The numbers in brackets denote the number averaged. An allowance of 0.01 has been made for each star described as having a "small" proper motion in Innes' catalogue. It will be noted that it is the fainter stars that have the proper motions above the average.

This apparent large proper motion of double stars is worthy of more attention than seems to have been given to it.

WEYMOUTH, ENGLAND,
December 1, 1902.

THE ORBIT OF THE SPECTROSCOPIC BINARY η *ORIONIS.*

By WALTER S. ADAMS.

THE variation in the radial velocity of η *Orionis* was discovere at the Yerkes Observatory in December of 1901, and announce at the Washington meeting of the Astronomical and Astrophysical Society during that month. The star has been on the regular observing list since that time, and sufficient material has bee secured to make an accurate determination of its orbit possibl

The star belongs to the class of binaries in which one component is relatively dark, as no certain evidence of superpose spectra has been found on any of the photographs. The spectrum is that of the *Orion* type, but contains, in addition to th regular helium and hydrogen lines, three silicon lines, and number of lines due to oxygen and nitrogen which have prove of great value in determining the star's velocity. In genera the lines may be said to be slightly better for purposes of measurement than in the case of the average star of this type, thoug still rather ill-defined and diffuse. At some points in the star' orbit the change in its radial velocity is so rapid as to amount t several kilometers in the course of the exposure required t photograph the spectrum, and this, no doubt, influences to a considerable degree the character of the lines upon the plates take at such times.

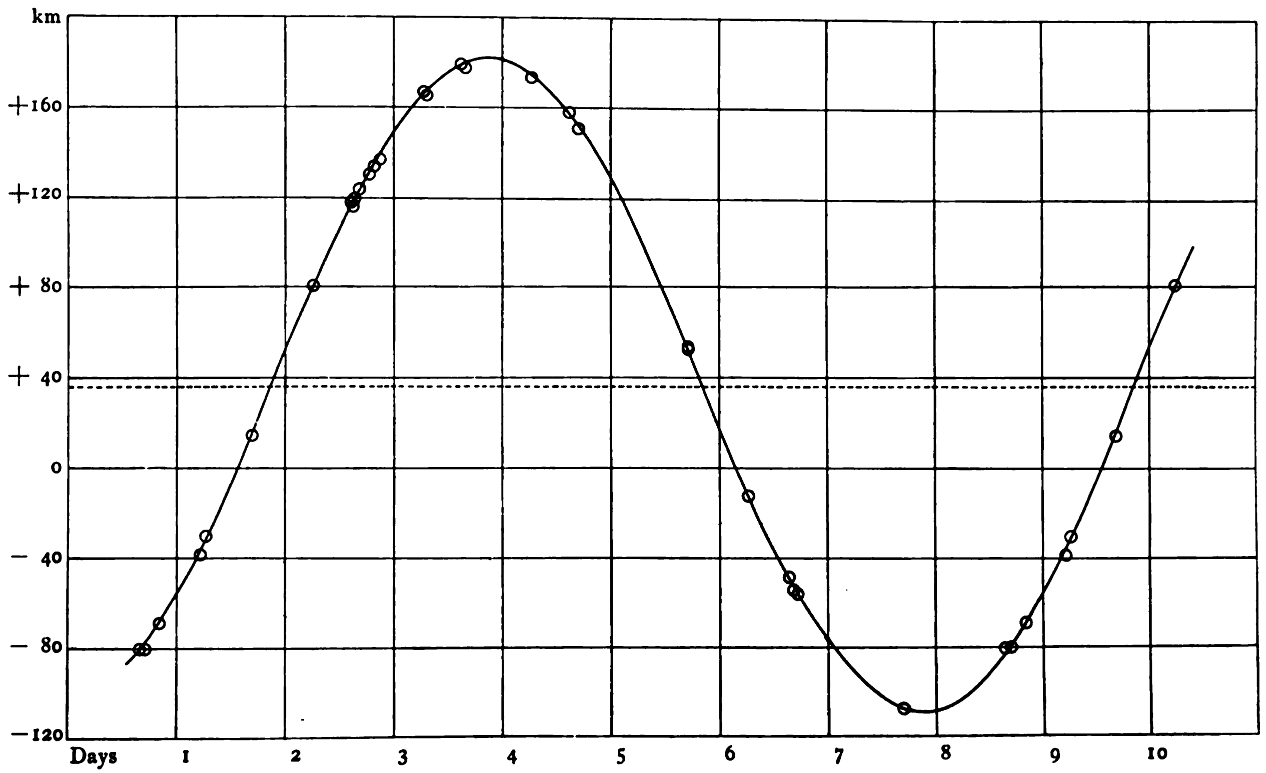
The number of lines measured upon the different plates varie considerably, but in the great majority of cases is from eight t ten. A careful examination of the cases in which more or les lines have been measured has led to the conclusion that an attempt to make a distinction in the weight given to a plat according to the number of its lines would be fully as liable t introduce error as to eliminate it, and accordingly unit weigh has been assigned in each case. So far as the individual line are concerned, however, the method has been adopted of assign

Plate No.	Date G. M. T.	Velocity	O.–C.
		km.	km.
B 251	1901, November 27.846	– 68.9	–0.6
A 294	December 6.691	+ 14.6	–1.8
B 256	December 18.703	+ 54.4	+1.9
A 296	December 19.676	– 53.7	–0.5
B 260	December 31.585	+115.9	–1.0
B 265	December 31.835	+136.6	–2.4
A 299	1902, January 4.691	– 55.1	+1.2
A 305	January 8.722	+130.0	0.0
B 269	January 9.568	+179.0	+0.1
B 274	January 16.547	+117.6	+2.2
B 279	January 16.762	+133.1	–1.6
A 309	January 22.590	– 80.5	+0.6
B 283	January 24.569	+119.8	+1.3
A 310	February 10.565	+177.8	–1.9
A 315	February 11.525	+158.5	+0.1
A 316	February 12.629	+ 53.1	+1.1
A 321	February 19.598	+151.0	–2.0
A 326	February 21.549	– 47.9	+1.3
B 296	March 13.564	+123.9	+0.2
A 339	March 27.563	– 80.0	–2.6
B 309	April 3.542	–106.5	0.0
B 405	September 3.908	– 29.5	+0.4
A 372	September 4.892	+ 80.5	+1.6
B 411	September 13.901	+166.6	+0.8
B 416	October 8.860	+173.6	–1.9
B 426	October 15.888	+165.0	–2.2
B 448	November 6.769	– 38.1	–2.6
B 460	November 19.822	– 11.8	0.0

All of the above measures were made by Adams with the exception of those of B 269 and B 309, which are the means of measures by Frost and Adams. Plate B 279 was measured twice, and the value given is the mean of the two determinations.

The method used in the derivation of the orbit was that of Lehmann-Filhés, although the very low value of the eccentricity would' no doubt, have made some of the methods using developments in power series equally applicable. The observations were plotted on millimeter paper with a period of $U = 7.9896$ days, and a smooth curve was drawn through them subject to the condition that, after an abscissa had been constructed, making the areas above and below it equal, the adjacent areas included between the maximum and minimum ordinates, the abscissa, and the curve should be equal. The areas in question were adjusted by means of a planimeter, and the following quan-

PLATE III.



Light Curve of η *Orionis.*

tities were obtained as a basis for the computation of the elements:

Velocity of system $V = +35.5$ km.
$A = 146.5$ km; $B = 143.0$ km; $z_1 = +1.35$; $z_2 = -1.38$.

The unit in the cases of z_1 and z_2 is arbitrary, as their ratio alone is required. The notation is that of Lehmann-Filhés.

The elements derived from these quantities are as follows:

$u_1 = 90^\circ\ 41'.6$
$\omega = 42^\circ\ 16'$
$e = 0.016$

$\log \mu = 9.89566$ or,
$\mu = 45^\circ.059$
$T = 1901$, December 1.821
$a \sin i = 15{,}901{,}000$ km.

Owing to the very low value of the eccentricity, ω and T are the most uncertain of these elements, but even in these cases the errors should not be large.

An ephemeris was computed with these elements, and the differences between the observed and the computed velocities are given in the column O. – C. of the table above. In view of the character of the spectrum measured, these residuals are entirely satisfactory. A least squares solution might reduce them slightly, but as no significance is to be attached to fractions of a kilometer in measures of stars having this type of spectrum, it has not seemed desirable to undertake it. The accompanying diagram shows the curve derived from the set of elements, and the positions of the observed velocities in reference to it. Owing to the high velocities involved, the scale is necessarily small, but the general agreement of the values is well shown.

In conclusion attention may be called to the fact that η *Orionis* is also a visual double star with components of the fourth and sixth magnitudes. It is, of course, with the brighter of these that we are dealing here.

YERKES OBSERVATORY,
December 20, 1902.

HERSCHEL'S NEBULOUS REGIONS.[1]

By ISAAC ROBERTS.

WILLIAM HERSCHEL'S observed nebulous regions, fifty-two in number, are in this paper compared with the writer's photographs of the same regions, taken, simultaneously, with the 20-inch reflector and the 5-inch Cooke lens.

The nebulous regions referred to in the above title were described by William Herschel in a paper which he communicated to the Royal Society in the year 1811, and which was published in the *Philosophical Transactions*, Vol. **74**, under the heading "Construction of the Heavens."

So far as I can gather, no systematic efforts were made to verify Herschel's observations of these fifty-two regions until six years ago, when the work of photographing them was commenced at my Observatory, using for the purpose the 20-inch reflector and the 5-inch Cooke lens.

The photographs were taken in duplicate, simultaneously, with exposures of ninety minutes' duration, and at times when the objects were as near as practicable to the meridian and the sky clear during the exposure. The plates were selected and tested for sensitiveness, so that with the reflector the images of stars to about the seventeenth magnitude would appear on the plates and stars of about the fifteenth magnitude would appear on the plates exposed with the Cooke lens.

My long previous experience in photographing the heavens enabled me to judge that under these conditions nebulosity of at least the degree of faintness that could be seen by Herschel with his two- and four-foot reflectors would be shown on the photographic plates.

The tabular method adopted by Herschel in publishing the results of his telescopic observations enables me to give the photographic results in a concise and intelligible form, coinciding line by line with his, by comparing the headings and reading the descriptive matter relating to each object respectively.

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[1] The manuscript of this article was accepted by the editors on the supposition that it was not to be published in other current journals.

TABLE OF WILLIAM HERSCHEL'S FIFTY-TWO REGIONS.

Herschel's Nos.	R. A. (1900)	Dec. (1900)	Herschel's description in *Phil. Trans.*, 1811	Dates when photographs were taken	Isaac Roberts' descriptions of his photographs
1	0^h 10^m 8^s	9° 26′	Much affected with nebulosity	1900, Nov. 22	Sky clear ; stars small and faint, and few in number ; large areas void of stars ; no nebulosity on plate.
2	0 17 37	3 59	Much affected	1899, Sept. 5	Sky clear ; stars small and faint, and not very numerous ; large areas void of stars ; no nebulosity on plate ; film dark.
3	0 22 23	29 9	Affected	1899, Sept. 9	Sky clear ; stars small and very numerous ; one star of 5.9 mag., *B. D.* 28°.75, on plate ; small areas void of stars ; no nebulosity.
4	0 25 37	3 59	Much affected	1900, Nov. 22	Sky clear ; stars few and faint ; large areas void of stars ; no nebulosity on plate.
5	0 30 11	23 25	Much affected	1900, Oct. 27	Sky clear ; stars faint and numerous ; nebulæ H *III*, 476, and *N. G. C.* 169, d'Arrest and Ld. R., together with other fainter ones on plate ; many areas void of stars ; no diffused nebulosity.
6	0 36 28	0 29	Appeared to be affected with very faint nebulosity	1899, Oct. 28	Sky very clear ; stars small and very few in number ; large areas void of stars ; some small nebulæ on plate ; no diffused nebulosity.
7	0 38 0	41 10	Affected with nebulosity	1895, Oct. 17	Sky very clear ; stars crowded on plate ; many small areas void of stars ; several photographs have been taken of this region, which includes the great *Andromeda* nebula *M.* 31, part of the *n. f.* end of which would cross Herschel's field of view in this sweep.
8	0 39 27	39 16	Unequally affected	1900, Oct. 17	Sky clear ; stars crowded on plate ; many small areas void of stars ; part of *s. p.* end of *M.* 31 on plate ; no other diffused nebulosity.
9	0 41 19	43 30	Suspected faint nebulosity	1900, Oct. 26	Sky clear ; stars small and crowded on plate ; many small areas void of stars ; no diffused nebulosity.
10	0 48 38	43 35	Suspected faint nebulosity	1900, Oct. 26	Sky clear ; stars small and crowded on plate ; numerous areas void of stars ; nebula *N. G. C.* 317 on plate ; no diffused nebulosity.
11	1 41 8	29 48	Suspected to be tinged with milky nebulosity	1900, Nov. 27	Sky clear ; stars small and numerous ; large areas void of stars ; no nebulosity.
12	2 27 55	19 0	Much affected with nebulosity	1900, Dec. 13	Sky clear ; stars small and not very numerous ; large areas void of stars ; some very small and faint nebulæ on plate ; no diffused nebulosity.
13	4 2 14	25 11	Much affected	1901, Feb. 13	Sky very clear ; stars small and numerous ; large areas void of stars ; no nebulosity.
14	4 23 51	35 7	Suspected pretty strong nebulosity	1901, Feb. 13	Sky very clear ; stars small and crowded on *s.* and *s. p.* sides, but few on the rest of the plate ; large areas void of stars ; nebula H *I* 217 and also a tenth mag. star surrounded by very faint nebulosity 11′.5 *n. f.* H *I* 217 on plate ; no nebulous region.
15	4 24 51	35 8	Suspected nebulosity		
16	4 26 29	−7 30	Strong milky nebulosity	1901, Feb. 14	Sky clear ; stars small and very few on plate ; large areas void of stars ; no nebulosity.

TABLE OF WILLIAM HERSCHEL'S FIFTY-TWO REGIONS.—*Continued.*

Herschel's Nos.	R. A. (1900)			Dec. (1900)		Herschel's description in *Phil. Trans.*, 1811	Dates when photographs were taken	Isaac Roberts' descriptions of his photographs
17	4	29	2	20	50	Much affected	1901, Feb. 15	Sky very clear; stars small and very numerous; small areas void of stars; no nebulosity.
18	4	44	5	20	50	Much affected	1901, Feb. 15	Sky very clear; stars small and crowded on plate; small areas void of stars; no nebulosity.
19	4	52	17	26	45	Strong suspicion of very faint milky nebulosity	1901, March 9	Sky clear; stars small and very few; large areas void of stars; no nebulosity.
20	5	15	50	25	1	Very much affected	1901, M'ch 12	Sky clear; stars small and very few on plate; large areas void of stars; no nebulosity.
21	5	19	20	25	1	Affected		
22	5	28	53	-6	56	Affected with milky nebulosity	1901, M'ch 13	Sky clear; stars not very numerous; large areas void of stars; H *IV* 33 *Orionis* on plate; no nebulosity.
23	5	30	10	-2	43	Affected	1901, M'ch 12	Sky clear; stars small and very few; large areas void of stars; no nebulosity.
24	5	31	56	-4	18	Visible and unequally bright nebulosity. I am pretty sure that this joins to the great nebula in *Orion*	1902, M'ch 5	Sky very clear; stars small and not very numerous; areas void of stars; no nebulosity on plate.
25	5	35	34	-2	31	Diffused milky nebulosity	1900, Jan. 25	Sky clear; stars very numerous on *p.* half of plate, but few on *f.* half, where there are large areas void of stars; large cloud of nebulosity *n. f.* ζ *Orionis* with broad division void of stars, but with some nebulosity in *s. f.* to *n. p.* direction; other divisions break up the cloud into separate masses. To the *s.* of ζ is a stream of nebulosity, 54 minutes of arc in length, with an embayment free from nebulosity dividing it in halves. Another faint nebulosity extends from ζ 27 minutes of arc toward the *s.*, *s. p.* and *n. p.* The star *B. D.*—1°.1001 is in the midst of nebulosity, and it has a companion on the *s. p.* side. The star *B. D.*—1°.1005 is involved in a large cloud of streaky nebulosity, and it has a companion on the *p.* side. The star *B. D.*—2°.1345 is H *IV* 24, *N. G. C.* 2023; it is in the midst of a large, dense streaky cloud of nebulosity which has in it condensations and remarkable rifts free from nebulosity; near the *s.* end of one of these rifts is a twelfth magnitude star. The star *B. D.*—2°.1350 is in the midst of a cloud of nebulosity with some faint structure in it, and it has a companion on the *n. p.* side. The region here referred to, which covers four square degrees of the sky, has so many remarkable features that it is necessary, in order to make it intelligible to the reader, to present the photograph annexed along with the above description.

TABLE OF WILLIAM HERSCHEL'S FIFTY-TWO REGIONS.—*Continued.*

Herschel's Nos.	R. A. (1960)			Dec. (1900)		Herschel's description in *Phil. Trans.*, 1811	Dates when photographs were taken	Isaac Roberts' descriptions of his photographs
26	5^{h}	36^{m}	52^{s}	−6°	57′	A pretty strong suspicion of nebulosity	1901, Mar. 22	Sky clear; stars small and few; large areas void of stars; no nebulosity.
27	5	43	11	+1	8	Affected with milky nebulosity	1901, Mar. 13	Sky clear; stars very few in number; large areas void of stars; no nebulosity.
28	6	1	1	+3	44	Much affected.	1902, Jan. 29	Sky clear; stars crowded on *n. p.* and *s. p.* sides; large areas void of stars; no nebulosity.
29	6	0	54	-20	27	Affected	1902, Mar. 6	Sky clear; stars small and very numerous; many areas void of stars; no nebulosity.
30	6	40	7	41	16	Affected	1901, Mar. 22	Sky clear; stars few in number; large areas void of stars; cluster H. *VIII*, 71 on plate; no nebulosity.
31	9	27	32	−18	27	Affected	1902, Mar. 6	Sky clear; stars small and few in number; large areas void of stars; no nebulosity
32	9	36	43	71	13	Much affected with very faint whitish nebulosity	1901, Aprl. 12	Sky clear; stars small and numerous; several large areas void of stars: no nebulosity.
33	10	11	50	−9	3	Very faint whitish nebulosity	1901, Aprl. 15	Sky clear; stars small and numerous; large areas void of stars; no nebulosity.
34	10	22	25	51	32	Much affected	1901, Aprl. 13	Sky clear; stars small and not numerous; large areas void of stars; no nebulosity.
35	10	40	59	62	45	Affected with very faint nebulosity	1901, Aprl. 14	Sky clear; stars small and not very numerous; large areas void of stars; no nebulosity.
36	11	4	30	62	44	Affected	1901, Aprl. 15	Sky clear; stars small and numerous: areas void of stars; several small, faint nebulæ on plate; no diffused nebulosity.
37	12	2	5	30	37	Affected with whitish nebulosity	1901, Aprl. 17	Sky clear; stars small and few in number; large areas void of stars; H.*II*, 321, and H.*II*, 802, on plate; no nebulosity.
38	12	12	40	30	37	Affected with whitish nebulosity	1901, Aprl. 18	Sky clear; stars few in number; large areas void of stars; four small prominent nebulæ on plate; no diffused nebulosity.
39	13	12	15	34	8	Much affected	1901, Aprl. 17	Sky clear; stars not very numerous; large areas void of stars; no nebulosity.
40	14	2	20	34		Very much affected and many faint nebulæ suspected	1899, June 2	Sky clear; stars small and not numerous; areas void of stars; no nebulosity.
41	15	9	37	18	57	Affected with very faint nebulosity	1899, June 12	Sky clear; stars small and not very numerous; areas void of stars; no nebulosity.
42	21	3	26	−1	53	Much affected with whitish nebulosity	1902, Nov. 4	Sky clear; stars very numerous; no nebulosity.
								Herschel's sweep 42, as given in the *Phil. Trans.* (*R. A.* (1800), 20^{h} 58^{m} 20^{s} *N. P. D.* (1800) = 92° 17′) is not in sequence; as this may be due to a typographical error in one of the co-ordinates, a plate corresponding to *R. A.* (1800) = 20^{h} 38^{m} 20^{s}, *N. P. D.* (1800) = 92° 17′ was taken on Aug. 28, 1897, as follows:
							1897, Aug. 28	Sky very clear; stars crowded on plate; no nebulosity.
43	20	53	15	16	44	A good deal affected	1897. Oct. 20	Sky clear; stars crowded on plate; no nebulosity.

TABLE OF WILLIAM HERSCHEL'S FIFTY-TWO REGIONS.—*Continued.*

Herschel's Nos.	R. A. (1900)			Dec. (1900)		Herschel's description in *Phil. Trans.* 1811	Dates when photographs were taken.	Isaac Roberts' descriptions of his photographs
44	20	54	34	43	32	Faint milky nebulosity scattered over this space, in some places pretty bright	1896, Oct. 10	Sky very clear; stars crowded on parts of plate; large areas void of stars on others; Nebula, H. *V* 37, *N.G.C.* 7000 forms part of this region; the photograph shows it as a magnificent object. I have published a photograph of this region in Vol. II of *Stars, Star-Clusters* and *Nebulæ*, pl. 24. p. 155. and also in *Knowledge*, Nov. 1, 1898; a copy is also annexed to this paper.
45	20	57	34	−1	34	Much aeffcted with whitish nebulosity	1897, Sept. 21	Sky clear; stars small and numerous; no nebulosity.
46	20	56	55	43	16	Suspected nebulosity joining to plainly visible diffused nebulosity	1896, Oct. 10	Regions 44 and 46 are on the same plate; see description given above, No. 44.
47	21	5	8	14	21	Affected	1899, Aug. 6	Sky clear; stars small and crowded on plate; no nebulosity.
48	21	34	15	10	19	Much affected	1898, Oct. 12	Sky clear; stars small and numerous; areas void of stars; no nebulosity.
49	21	46	52	21	31	Affected	1899, Aug. 9	Sky clear; stars small and crowded; areas void of stars; no nebulosity.
50	22	57	24	25	45	Much affected	1898, Sept. 20	Sky clear; stars very numerous; areas void of stars; no nebulosity.
51	22	57	54	25	45	Affected		
52	23	0	17	29	17	A little affected	1902, Oct. 27	Sky clear; stars small and very numerous; areas void of stars; H.*II.*, 212, on plate; no diffused nebulosity.

CONCLUSION.

The final results of the correlation of Herschel's nebulous regions and my photographs can be given in a few words as follows:

Of the fifty-two nebulous regions described by Herschel, the photographs show diffused nebulosity on four of them only; there is no visible trace of diffused nebulosity on forty-eight of the areas, but on the remaining four, which are Nos. 7, 25, 44, and 46, respectively, in the table, there is nebulosity with remarkable characteristic features, and these are delineated upon three of the photographs, regions Nos. 44 and 46 being on one plate.

STARFIELD, CROWBOROUGH, SUSSEX,
November 1902.

PLATE IV.

NEBULÆ AROUND ζ *ORIONIS* (January 25, 1900).

PLATE V.

NEBULA HERSCHEL V 37 *CYGNI* (October 10, 1896).

DIFFUSED NEBULOSITIES IN THE HEAVENS.

By E. E. BARNARD.

IN the present number of this JOURNAL there is a paper by Dr. Isaac Roberts containing an account of a photographic investigation of certain regions of the sky supposed by Herschel to be affected with diffused nebulosity. This investigation was made simultaneously with Dr. Roberts' 20-inch (51 cm) reflector and 5-inch (12.7 cm) Cooke portrait lens. The exposures given by Dr. Roberts to test the existence of these diffused nebulosities was ninety minutes, which, it is stated, showed stars of the sixteenth and seventeenth magnitudes. Out of these fifty-two regions he found only four that showed any traces of nebulosity. These four regions, however, had already been shown by numerous photographs to be nebulous. One of these, the great nebula north of *α Cygni*, was first photographed by Dr. Max Wolf some twelve years ago and has lately been called by him the "America Nebula"[1] from its striking resemblance to North America as shown on maps and globes.

The curious nebulous ribbon extending southward from ζ *Orionis* seems to have been first photographed by Professor W. H. Pickering and others as far back as 1889.

This question of large areas of diffused nebulosity in the sky is a very important one, not yet fully appreciated, but which must sooner or later have the highest bearing on a proper understanding of the physical condition of the universe. Dr. Roberts' negative results are so sweeping in character that it is highly important that anything tending to prove the existence of any of these questioned regions of nebulosity should be brought forward at once.

First, I do not think 90 minutes a sufficient exposure to test the existence of some of these nebulosities with Dr. Roberts'

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[1] The "North America Nebula" would perhaps be more definite, for it is North America to which Dr. Max Wolf intends the compliment.

outfit. The photographing of sixteenth or seventeenth magnitude stars does not necessarily prove that the same exposure ought to show diffused nebulosities, for photographing faint stars often stands on an entirely different footing from photographing faint nebulosities.

Second, it is a little unreasonable to suppose that Herschel, who made so few blunders compared with the wonderful and varied work that he accomplished, should be so palpably mistaken in forty-eight out of fifty-two observations of this kind.

I have myself been very much interested in the diffused nebulosities of the sky and have independently come across some of these very regions of Herschel, besides others not noted by him. It has been a long-cherished desire of mine to investigate them further photographically, and I now hope to be able to put this desire into a practical reality within the next twelve months. Some of these regions I have already shown to be extraordinary features of the sky — as instances, the nebulous regions of 15 *Monocerotis*, of ρ *Ophiuchi*, the region surrounding the *Pleiades*, etc. All of these were known to me previous to their really being proved by the photographic plate and the portrait lens to be true nebulosities.

As far back as January 1892, in *Knowledge*, **15**, 14–16, I called special attention to these nebulous regions of Herschel and gave the table contained in Dr. Roberts' present article. Attention was called to these objects as being suitable for photographic investigation in these words:

> It would appear that this table of diffused nebulosities will just now be of extremely great value, as it at once points out to those interested in photographing such objects, the proper pointings of their exposures. I have taken the liberty to copy the foregoing table in full for the benefit of those not familiar with it and who may wish to try exposures on these objects.

What leads me to hope that more of these regions given by Herschel may yet be shown to be nebulous with photographic plates, is that one of these very objects, which the photographs of Dr. Roberts show to be free from nebulosity, is really the brightest portion of one of the most extraordinary nebulæ in the sky, as shown by photographs made by two independent observers with three different photographic telescopes on several different occasions. I refer to region 27 of the list. This is described by Herschel as being "affected with milky nebulosity" and its position given for 1800.0 as α 5^h 38^m 5^s; P. D. 88° 55′.

The right ascension and declination for 1900.0 would be closely

$$\alpha = 5^h\ 43^m\ 13^s;\ \delta = +1^\circ\ 8'.$$

Dr. Roberts' note on this is: "Sky clear; stars very few in number; large areas void of stars; no nebulosity."

In *Popular Astronomy*, **2**, 151–154, December 1894, the writer has given some experiments with a very small magic lantern lens in photographing diffused nebulosities. In this an account is given of the finding of a great nebula extending in a curved form over the entire body of *Orion*. The brightest portion of the nebula is near 56 and 60 *Orionis*. From the photographs, the position of this brightest portion is in

$$1900.0\quad \alpha = 5^h\ 43.7^m;\ \delta = +1^\circ\ 0'.$$

This would make it identical with Herschel's No. 27. These pictures were made with an ordinary child's magic lantern lens, of 1.5 inches diameter and 4.9 inches equivalent focus. The exposures were 1894, October 3, for 2^h 0^m, and October 24, for 1^h 15^m. The shortest exposure, 1^h 15^m, showed it best. I suppose a half-hour's exposure would have shown traces of it. Unknown to me at the time, this nebula had already been photographed in 1889 by Professor W. H. Pickering on Mount Wilson (altitude 6,250 feet) in southern California, with a Voigtlander portrait lens of 2.6 inches aperture and 8.6 inches equivalent focus, with an exposure of three hours.[1]

Besides the photographs made with the magic-lantern lens, I have two made with the six-inch Willard portrait lens that show portions of the nebula distinctly. They were made 1893, October 17, with 3^h 0^m exposure; and 1894, October 3, with 2^h 0^m exposure. In both the photographs with the Willard lens, the region of the nebulosity falls near the edge of the plate and hence the stars are deformed. At the time of making these

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[1] See *Sidereal Messenger*, **9**, 1, 1889.

pictures I knew nothing of the existence of this object and therefore had no choice as to its location on the plate. One of these photographs has been selected for reproduction, though it will necessarily be unsatisfactory because of the position of the object close to the edge of the plate.

[Through the courtesy of the editor of *Popular Astronomy*, the map of *Orion* showing the location of the nebula is here reproduced. (Plate VI, A).]

To further show the reality of the nebulous region No. 27 of Herschel's list, I made an exposure of $2^h\ 10^m$ on the night of January 17, 1903, on the region with a small, cheap lantern lens belonging to Professor Hale. This lens is 1.6 inches in diameter and has an equivalent focus of 6.3 inches or $\frac{a}{f}=\frac{1}{4}$.

The sky was clear and the conditions fair. The resulting negative showed a fairly good field of nearly 25°.

Most of the great curved nebula is clearly shown, especially the region described by Herschel, which is now in question and which, as I have said, is the brightest portion of the nebula.

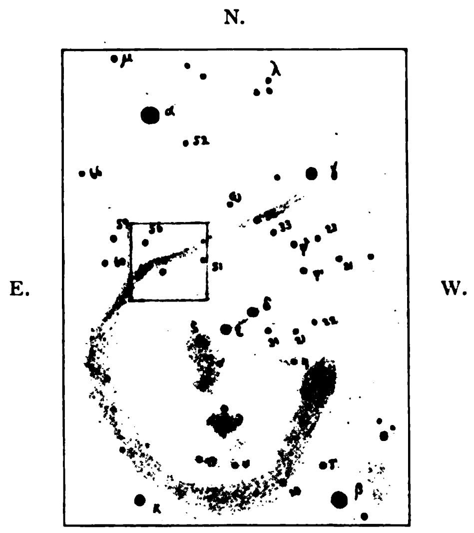
This plate does not show the nebula as strongly as those made with the lantern lens used by me at the Lick Observatory, because, for one reason, the present lens is relatively of smaller angular aperture, $\frac{1}{4}$ as compared with $\frac{1}{3.2}$; and for another reason the sky was not perhaps as pure; but the main portion of the nebula is conspicuous. There is therefore no question but that this nebulosity exists where Herschel saw it.

Just what the faintest stars are that appear on this plate I am not prepared to say, not having had any chance to make a comparison with the sky; but they are certainly several magnitudes brighter than the fifteenth or sixteenth magnitude.

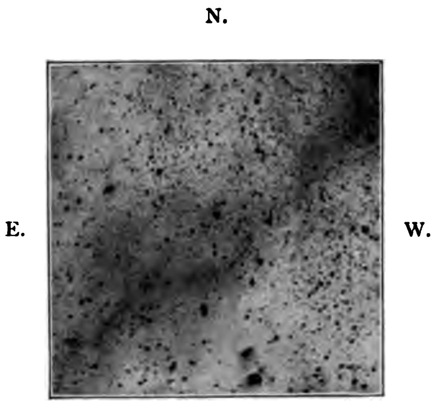
It was with the same instruments described in his present paper that Dr. Roberts failed to get any traces of the exterior nebulosities of the *Pleiades*, which have been shown by four observers with four different instruments not only to exist, but to be not at all difficult objects.

YERKES OBSERVATORY,
January 1903.

PLATE VI.



A.



B.

The Great Curved Nebula in Orion.

A.—Drawing from two lantern lens photographs (Oct. 3 and 24, 1894).

B.—Photograph, with Willard lens, of region inclosed in the square in the drawing above (Oct. 17, 1893).

MINOR CONTRIBUTIONS AND NOTES.

NEW COLLABORATORS OF THE ASTROPHYSICAL JOURNAL.

THE ASTROPHYSICAL JOURNAL has from the outset enjoyed many advantages from the cordial co-operation of eminent investigators at home and abroad. The list of collaborators includes many of the ablest representatives of the branches of science with which the JOURNAL is most directly concerned. On the death of M. Cornu, who had assisted the JOURNAL in many ways, Professor Bélopolsky kindly accepted an invitation to fill the vacant place. As the editors have always desired to maintain a fairly even balance between the physical and the astronomical sides of the subject, they now take special pleasure in announcing that Professor Kayser and Professor Runge have signified their willingness to serve as collaborators. With this added strength on the laboratory side, the JOURNAL will continue to emphasize the importance of treating celestial and terrestrial problems of radiation from a single point of view.

A CONTRIBUTION TO THE KNOWLEDGE OF SPECTROSCOPIC METHODS.[1]

THE investigation undertaken by Dr. Konen proposes to test the method of the electric discharge under liquids as a means of solving the important problem of the origin of band-spectra. His paper touches upon the difficulties which presented themselves to former investigators — notably the transitory nature of band-spectra, their faintness, and the difficulty of ascertaining just what element or elements were essential to the production of any given spectrum; it mentions the methods and apparatus previously employed — namely, Geissler tubes and a flame or a carbon arc in closed receptacles; and states that we should expect this method of discharge under liquids to present fewer difficulties owing to the presence of fewer impurities.

The discussion of the *arc* discharge is preceded by a brief résumé

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[1] Abstract, by Norton A. Kent, from advance proofs (furnished by the author) of a paper to appear in *Annalen der Physik.*

of the work of Davy, Masson, and Liveing and Dewar; and attention is called to the fact that very few investigations other than visual have been made upon this subject. The apparatus used by Konen consisted of a glass vessel silvered within, blackened without, and fitted with a quartz window. The pole pieces were held in brass clamps. The current employed varied from 15 to 20 amperes (below 15 the arc ran poorly, while above 20 the liquid was unnecessarily heated). The light passed through a quartz window and was focused by a quartz lens upon the slit of (1) a Steinheil prism (flint glass) spectroscope, in the first part of the investigation, and (2) later and in most of his work, a Rowland concave grating of one meter radius of curvature, rigidly mounted and used in the first spectrum — the extent of region covered being from $\lambda 5500$ to $\lambda 1800$. The spectrum was photographed on films.

As a result of the tearing asunder of the electrodes, the immersing water is rendered turbid, especially so where carbon or iron poles are used; all liquids are befouled sooner or later; water, alcohol, and electrolytes last the longest; some liquids admit of filtration; all clear by standing.

Besides a continuous spectrum there are always present (1) the H and K lines of calcium, also generally other lines of the calcium spectrum; (2) the two chief aluminum lines; and (3) the D lines of sodium. With metal poles Fe, Cu, Ba, Na, K, Li, Tl, and brass, the characteristic line spectra appear — but band spectra never. The liquid-arc lines are generally fully as sharp as those of the air-arc; many are sharper. The relative intensity varies and some air-arc lines are wholly absent in the liquid-arc spectrum. No displacement is apparent. The nature of the surrounding liquid has no influence upon the spectrum given by metal poles — this being true for alcohol, distilled water, and glycerine — and, with certain reservations, for salt solutions. In concentrated $BaCl_2$ and $CaCl_2$ solutions the strongest barium and calcium lines are present, but they are incomparably weaker than in air, and only the strongest calcium lines are reversed. The effect is not a function of decrease of temperature, nor of the behavior of the poles, *i. e.*, whether merely a single point or the whole pole glows. The probable physical and chemical processes which take place when carbon poles are used in a $NaCl$ solution is as follows: Near the poles the liquid is in the spheroidal shape; the $NaCl$ remains in solution; the glowing carbon and the water vapor react to produce CO and H etc.; and these gases form the medium in which the true arc burns

Vaporized liquid surrounds these gases, being forced aside by the latter, which are better conductors by reason of their hotter and ionized condition. Only the gases of the poles enter. This is further shown by the use of cored carbons filled with salt — an arrangement which gives the sodium spectrum.

The problem of the origin of the so-called carbon and cyanogen bands is then attacked. The carbon arc in air gives bands whose edges lie at λ 4606.33, 4216.12, 3883.55, 3590.48. These are generally ascribed to cyanogen. The band at λ 3883 photographs most quickly, and is therefore used as a test of the presence of the cyanogen spectrum. By using boiled water and boiled electrodes Konen succeeded in causing all four of these bands to disappear. Small amounts of air suffice to produce weak traces of them; therefore they will appear if unboiled carbons or conducting water be used, or if an excess of air be blown into the liquid, or, further, if the arc be submerged in strong water solutions of ammonia. In alcohol and CCl_4 the "cyanogen" bands are lacking; in petroleum a trace of λ 3883 appears when the poles used have been made from carbon rods glowing under aniline. In KNO_3 only traces appear — even weaker than those given by water containing air. But in view of what has been said of the part played by salt solutions in the development of the arc, this negative result is not surprising. *In every case the presence of nitrogen* is necessary to the production of the bands in question. This forms a new proof that these four bands belong to cyanogen.

As to the origin of the Swan spectrum — a much-contested question for over fifty years — Stokes advanced the hypothesis that the so-called "carbon" band spectrum belonged to carbonic oxide — an hypothesis the truth of which Konen considers not yet rigorously proven.

To facilitate the discussion of this question six classes of spectra are distinguished :

1. A continuous spectrum without bands or lines.
2. A line spectrum.
3. The cyanogen spectrum with edges at λ 3590, 3883, 4216, and 4606.
4. The so-called "carbon" band, or Swan spectrum, with principal heads at λ 4382, 4738, 5164, 5633, and 6187.
5. The so-called "carbonic oxide" spectrum with edges at λ 4509, 4834, 5196, 5608, 6078, 6399, 6622.
6. The carburetted hydrogen flame spectrum with edges λ 4315, 4368, 3872, and 3627.

The condition under which the first three appear are briefly given. No. 4 appears with No. 6 in the carburetted hydrogen flame; in the arc in air and different gases; in the liquid arc under certain conditions; in vacuum tubes filled with carburetted hydrogen; in the cyanogen flame; in carbon-dioxide gas at moderate pressures; in tubes during the first part of the discharge in carbonic-oxide gas; in the brush discharge in alcohol, glycerine, ether, acetic acid, etc.; in the Sun; and, doubtfully, in numerous other instances. The Swan spectrum is absent in the CO and CS_2 flames. No. 5 is obtained from an impurity in Geissler tubes; in CO and CO_2 tubes; also with oxygen or air in various carbon compounds. It is absent in the CO and CS_2 flame, and in the spark of hydrogen or water vapor. No. 6 is obtained only by burning carburetted hydrogen with oxygen in, *e.g.*, a Bunsen flame. It is absent in the spark discharge between carbon electrodes in air, CO_2 and H; also when No. 4 is strongly present. It is a remarkable fact that most observers have identified the flame or Swan spectrum with No. 4.

Spectrum No. 4 is then discussed. The question of its origin is connected closely with that of No. 5. The points to be settled are: Does the spectrum belong to (1) carbon itself; (2) to the positive ion of carbon in an ionized state; (3) to a hydrogen compound of carbon; or (4) to an oxygen compound—*i.e.*, to CO? (1) and (2) may be treated together. The results obtained with cyanogen and water, etc., show that (3) is out of the question. Moreover as no rule has been found whereby a certain spectrum may be shown to be due to one of two components, or to the "completed compound," or to all these together, it is clear that some uncertainty must enter into the proof that a definite compound causes that spectrum. In the light of this reasoning Smithell's investigation, in which he sought to explain the behavior of CO and CO_2 by different degrees of dissociation, is very artificial and, at best, hypothetical. If it cannot be shown indubitably that the spectrum in question comes from a finished product, then the proof that it is caused by the presence of CO, for instance, means no more than that one or the other element is essential.

The real question is: "Is the presence of oxygen necessary to the formation of the 'carbon' band-spectrum?" Two experimental difficulties are present. An affirmative result—the presence of a certain band in a given case—admits of no conclusion; while the value of a negative result—the absence of that band—depends wholly upon the sensitiveness of the spectral reactions. If this limiting sensitiveness be passed it is practically and chemically impossible to exclude th presence of a definite substance. But it is possible to establish one limit showing how much of an impurity must be present to produce a given spectrum, and another showing how much can be present without being active spectroscopically. Only within such bounds has the following experiment any meaning; and it *cannot presume to lead to a decision in the question of the origin of spectra 4 and 5.*

Metal and carbon poles were used. The latter were placed in a glass tube attached to a mercury pump; the air was exhausted, the tube steadily heated, and an electric discharge — as strong as possible — was passed between the pole pieces. Then the tube was sealed off and broken open beneath the surface of a testing liquid; the terminals were then placed in position, boiled in liquid, and covered with a layer of graphite by the action of the arc discharge — a result most easily accomplished by the use of aniline. The liquids used — water, salt solutions, alcohol, glycerine, carbon tetrachloride, aniline, carbon bisulphide, petroleum, and ammonia — were chemically pure and, as far as possible, were preserved over phosphorous pentoxide in the dark. In distilled and conducting water, spectrum No. 4 appeared complete. As was suspected, *CO* is developed in large amounts. An air-blast made no difference. The same is true for alcohol, glycerine, and ammonia. The bands are less intense than in air. Metal terminals cause a further weakening. In some liquids, *e. g.*, very strong salt solutions, the bands can be blotted out. It is well known that in air the introduction of metals weakens the carbon and cyanogen bands. In both cases it is quite appropriate to explain the phenomenon in accordance with the *CO* hypothesis, as a process of oxidation in which the metal seizes the oxygen. The temperature of the carbon poles under water plays a part. With metals this temperature is visibly less, as is clear from the smaller consumption of carbon and the shrinking of the heated area of the pole, and it is in precisely these instances that the carbon bands are lacking. Carbon bisulphide fogs quickly, permitting only visual observations. In all cases the carbon bands are unquestionably present. In aniline bands appear at λ 56, 51, and 47, but the decomposition produces such strong absorption near λ3883 that that region of the plate is not affected at all, and the cyanogen band therefore does not appear. In carbon tetrachloride these three bands are stronger than in aniline; they are most intense in petroleum and here a trace of λ3883 appears, while the bands of spectrum No. 6 as well as all lines are absent. Visual observation of carbon bisulphide, chloroform, and turpentine give the same result, apart from the continuous spectrum the green band alone is present, and it only faintly.

If the sensitiveness of the arc to traces of water or oxygen is small enough, then the deduction may be drawn that "the presence of oxygen is not necessary for the production of spectrum No. 4. The old theory is then confirmed — *the so-called carbon band-spectrum rightly deserves its name.*"

On the other hand, we must emphasize the impossibility of keeping the carbon rods and the liquids free from oxygen; and, if we rate higher the sensitiveness of the liquid arc, we must abstain from any conclusion. If the existence of impurities is assumed, an exceptional position must be conceded to oxygen and carbonic acid.

Dr. Konen discusses other forms of discharge in liquids, namely, the *glow*, *brush*, and *uncondensed* and *condensed sparks*. The points of greatest interest in connection with the subject in hand are that with the *brush* discharge in ether, alcohol, and solutions of iodine or bromine in ether, the Swan spectrum is obtained in an especially beautiful manner. In the arc the electrodes were the important element, in the brush discharge the liquid is. "The only deduction possible 'from brush discharge experiments' must take the form of a reiteration of the statement made regarding the results of the carbon arc."

With the *condensed spark* it is impossible with water, ether, alcohol, and salt solutions, and either carbon or graphite electrodes, to obtain traces of the carbon or cyanogen spectrum; and here, as with the arc, salt solutions have no effect. With a 9.5 per cent. $BaCl_2$ solution and Fe terminals Konen obtained a bright line spectrum where Hale had found an absorption spectrum.

H. KONEN.

FIRE AT THE YERKES OBSERVATORY.

DURING the past two years a horizontal reflecting telescope, to be used with a cœlostat of 30 inches aperture, has been in process of construction at the Yerkes Observatory. In conjunction with the instrument a large concave grating spectrograph had been provided for photographing stellar spectra. On December 22, when the final adjustments of the spectrograph were being made, the building caught fire from the breaking down of the insulation of the wires connected with the comparison spark apparatus. Under ordinary circumstances the small blaze thus produced might easily have been extinguished. But it had been necessary to construct the constant-temperature spectrograph house and the building containing the telescope as cheaply as possible as very little money could be obtained for the purpose. For this reason building paper and wood, with intervening air spaces, had been employed. This burned so rapidly that although the fire extinguishers were at once brought into action the flames were past control. In spite of the best efforts of the members of the Observatory staff, the buildings were destroyed, together with the new spectrograph and the 30-inch plane mirror, driving-clock, and all the smaller parts of the cœlostat. A second plane mirror of 24 inches aperture was saved, but the 24-inch concave mirror of 62 feet focal length was destroyed.

The house containing the horizontal telescope was situated at some distance from the main Observatory building, which was not damaged in the least.

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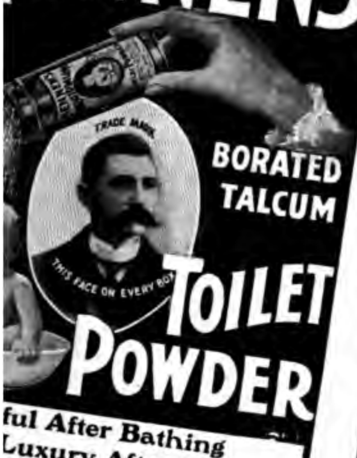
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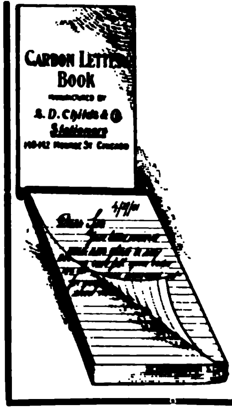
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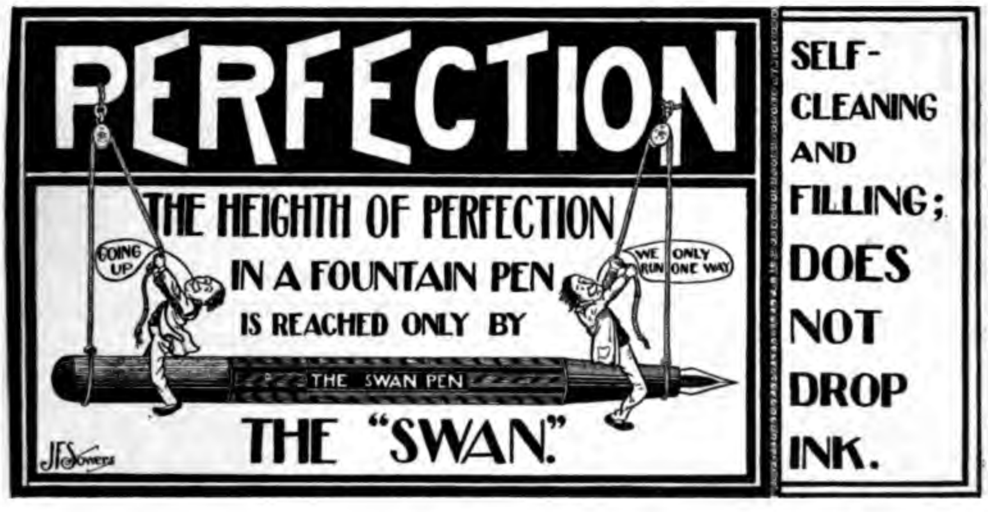

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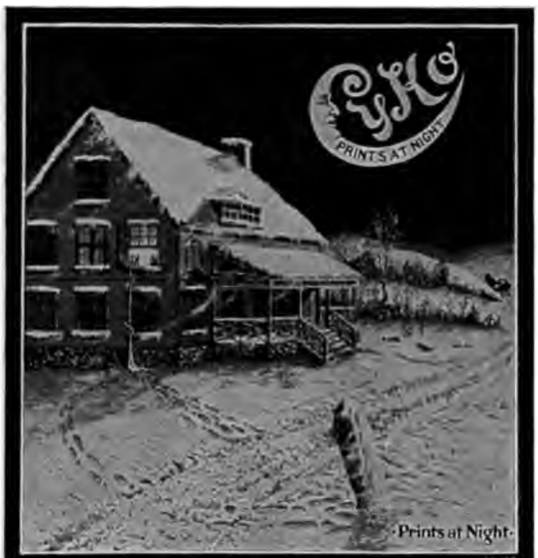

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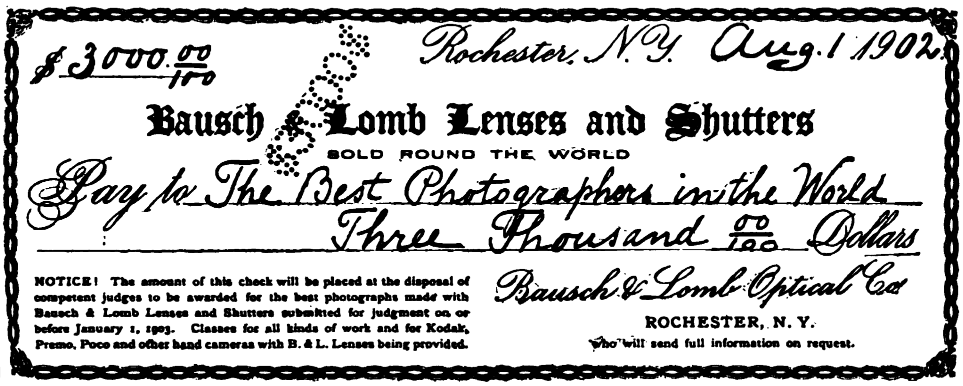

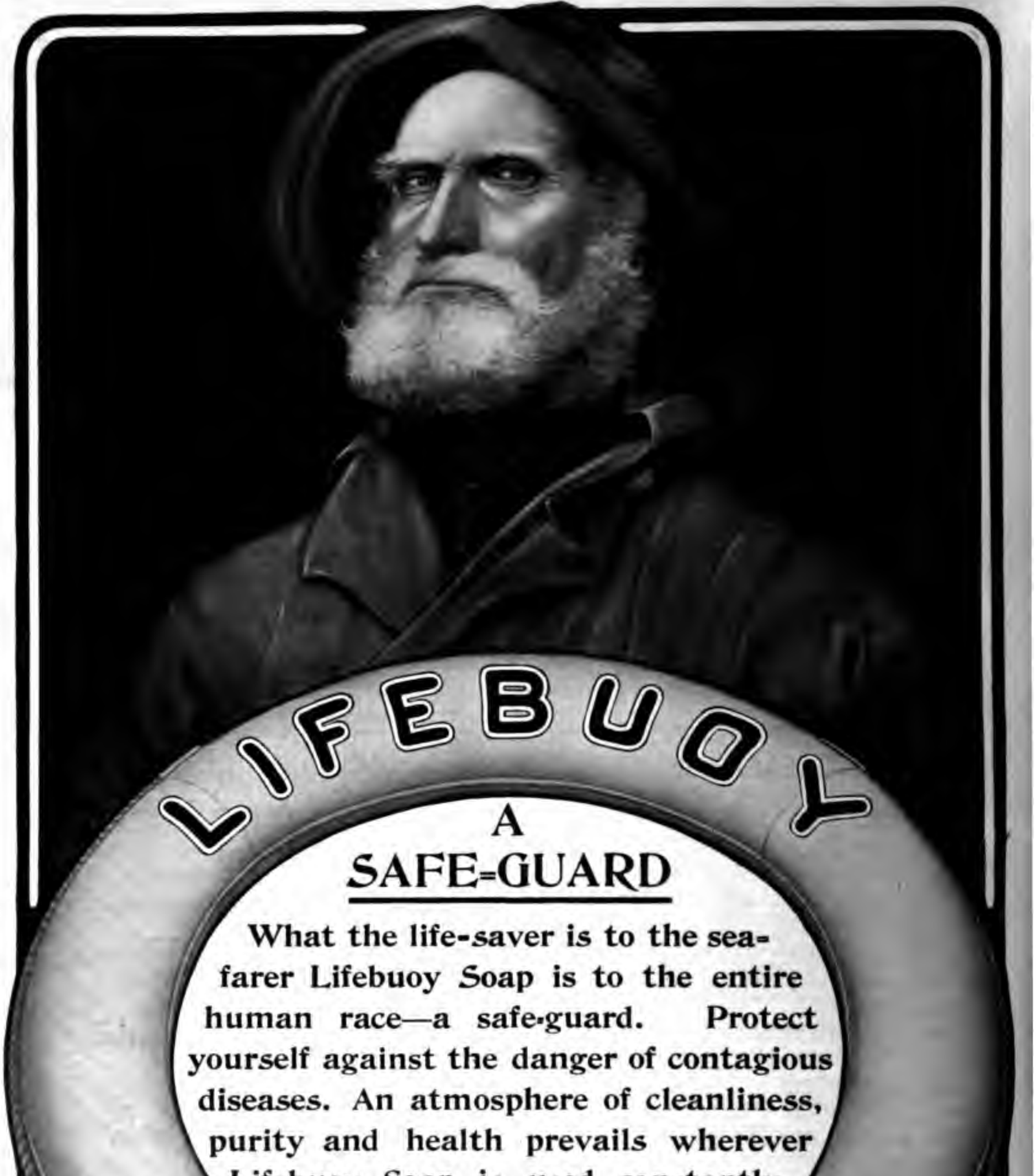

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VOLUME XVII NUMBER 2

THE ASTROPHYSICAL JOURNAL

An International Review of Spectroscopy and Astronomical Physics

EDITED BY
GEORGE E. HALE AND EDWIN B. FROST
of the Yerkes Observatory

MARCH 1903

CONTENTS

CHICAGO
𝔗𝔥𝔢 𝔘𝔫𝔦𝔳𝔢𝔯𝔰𝔦𝔱𝔶 𝔬𝔣 ℭ𝔥𝔦𝔠𝔞𝔤𝔬 𝔓𝔯𝔢𝔰𝔰
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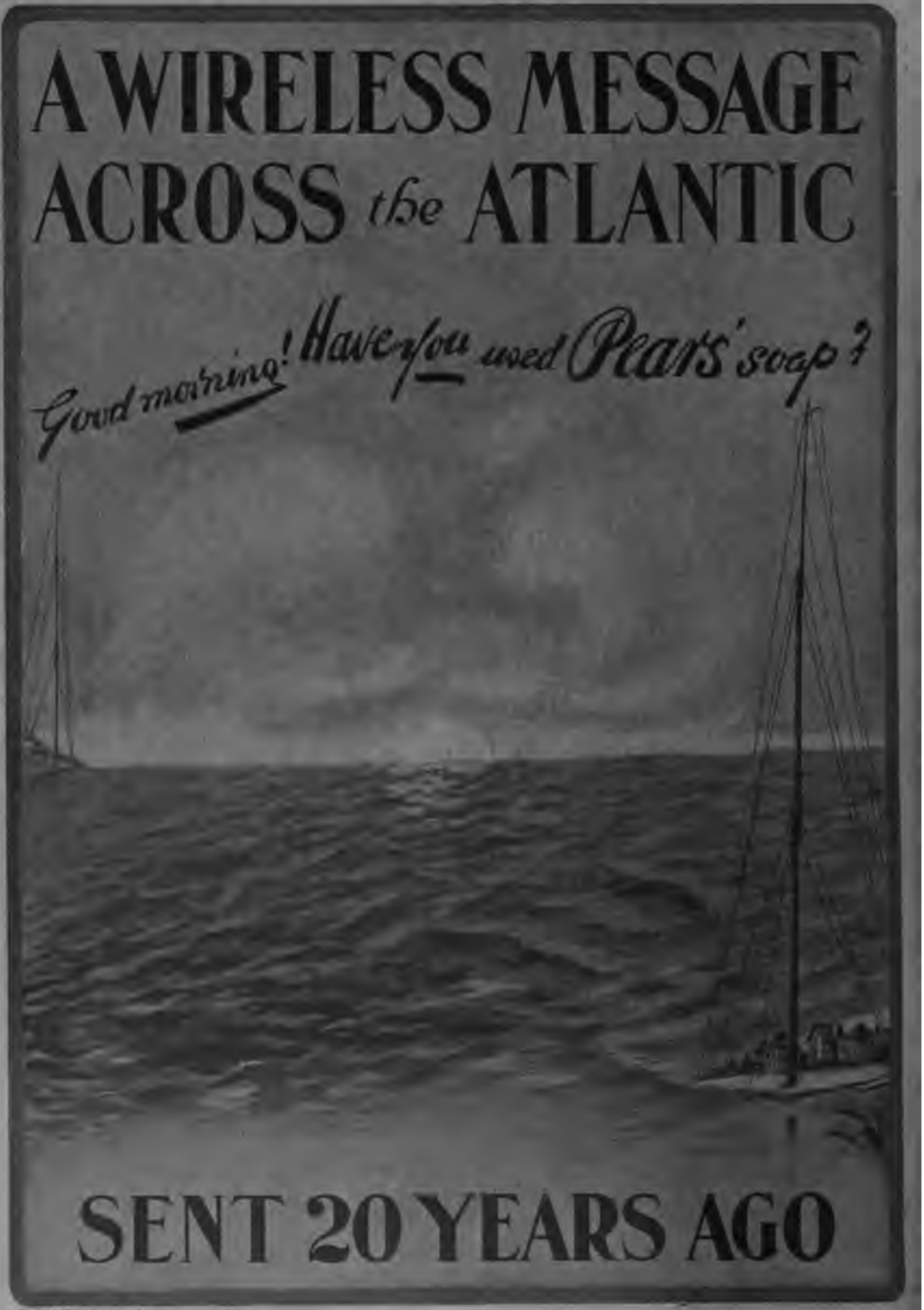
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THE
ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOL. XVII MARCH 1903 NO. 2

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THE
ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME XVII MARCH 1903 NUMBER 2

THE "SOLAR CONSTANT" AND RELATED PROBLEMS.[1]

By S. P. LANGLEY.

PHYSICAL astronomers, armed with new methods and perfected appliances, are helping us to a view of the progress of creation, from its beginning in the nebula, which must interest every student of nature. But however much our attention is aroused by the purely scientific aspect of such general studies, we must, it seems to me, consider, in the case I have now to present, *utility*, even before abstract interest. I refer to the study of the Sun, for though the most unformed nebula may hold the germs of future worlds, yet for us these possibilities are but interesting conjectures. For, as I have said elsewhere, I recognize that every nebula might be wiped out of the sky tonight without affecting the price of a laborer's dinner, while a small change in the solar radiation may conceivably cause the deaths of numberless men in an Indian famine.

From the foundation of the Smithsonian Astrophysical Observatory until now, I have therefore directed its work

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[1] Read before the Washington meeting of the American Association for the Advancement of Science, December 30, 1902.

toward solar study, with a view to its probable utilities as well as to its purely scientific value, while still regarding this last as of high importance.

While the Sun, then, can be viewed merely as the nearest and most accessible star, yet it is here considered in a more important aspect to us, as the source of the radiation on which all human life depends.

1. *Early work at the Allegheny Observatory and on Mount Whitney.*—Some twenty years ago it was my good fortune to devise a successful means of measuring those minute quantities of heat on which depends an accurate determination of the possible variation in the enormous quantities which the Sun sends the Earth. This instrument, the bolometer, I used for nearly a decade at the Allegheny Observatory in the investigation of the Sun. It early appeared that many questions of the gravest importance, especially that of the so-called "solar constant," depended for their solution on the observer's stationing himself as high above our lower air as practicable. Accordingly, when through public and private channels the necessary means were at length provided, I conducted an expedition to Mount Whitney, in southern California. This expedition was provided with such essentials of a solar observatory as could be gathered and transported with the limited means at command, and was fortunate in including in its personnel the youthful Keeler, whose untimely end we all of us regret.

The observations secured at Mount Whitney confirmed my conclusion that the earlier values of the "solar constant" by Pouillet and others were too low. They had been obtained by the aid of the actinometer or the pyrheliometer—instruments which were made to father results that they were not strictly responsible for, through the use of wrong methods of extrapolation. It had been tacitly assumed that all solar rays are equally absorbed, or at least that all are similarly absorbed, in passing through successive layers of the Earth's atmosphere. Nothing could be more incorrect. Some large gaps are left in the spectrum where, for a range of wave-lengths as great as from the violet to the red, almost no energy remains after the solar beam has passed through half the layer of air between the Sun and sea level, and I have shown that the absence of the study of individual rays—a study since made possible by the bolometer—leads to an altogether too small value of the solar constant.

It was, in short, shown by these observations that the solar radiations must be analyzed and their amount measured wave-length by wave-length, and coefficients of atmospheric transmission worked out for narrow spectral regions, before any trustworthy value could be assigned to the solar radiation outside the Earth's atmosphere. It is satisfactory to see how thoroughly this view, novel enough then, has now been accepted. Its results[1] gave values of from 3 to 3.5 calories for the solar constant, thus nearly doubling the classical value, 1.76 calories, of Pouillet. They brought no certainty of the fixity of this so-called "constant," which, however, indications now lead us to consider as possibly variable, and one whose changes are not improbably of the deepest practical concern to us. Where the most elaborate determinations of a quantity by competent observers thus differ by nearly 100 per cent., it is evident that, if there be considerable real variations in this quantity, they may exist without detection.

Were there no intervening terrestrial atmosphere, we might determine these solar variations, if they exist, by observations made here; but the difficulties of such a research, when conducted anywhere through the Earth's actually intervening and changing atmosphere, are manifest, and in our actual station perhaps insuperable. I shall proceed to give an example of the best means at our command for overcoming them—means admittedly insufficient here, but which we may hope to employ later in a more favorable locality, at an elevated station. This done, it will remain to consider an independent method which, by direct study of the Sun's atmospheric envelope, holds out some possibility of success in detecting variations in the Sun's radiation, if these exist, even in our actually unfavorable conditions.

---

[1] See *Professional Papers, Signal Service*, XV, "Report of the Mount Whitney Expedition."

2. *Improvements in apparatus.*—Since the institution of the Smithsonian Astrophysical Observatory, almost every year has witnessed improvements of the apparatus employed for making solar energy spectrum observations, such as are necessary in the problems relating to the solar constant. The story of all these improvements is quite too long to tell here, but can be found in Vol. I of the Observatory's *Annals.*

In consequence of these changes, which have now occupied me so many years, with final success, where two years of my personal assiduous labor formerly passed (at Allegheny) in getting an imperfect picture of the distribution of the energy in the solar spectrum, extending from the violet down to a wavelength of 2.5μ—this can now be obtained with ease in fifteen minutes of time, by an almost automatic process.

This stretch of spectrum contains almost all the energy which reaches sea level, and includes many regions of powerful water vapor absorption. It extends into a portion of the infra-red entirely unknown before the time of the Mount Whitney expedition, and which was, in fact, discovered in my observations on Mount Whitney itself.

You see superposed upon this chart (Plate VII) before you five of the energy spectrum curves to which I have just referred. The curves were taken at intervals of about one hour in two different afternoons. You will note that, while the five are generally similar, the lower pair shows greater absorption by water vapor in the great infra-red bands.

3. *New work of the Smithsonian Observatory.*—Armed now with apparatus capable of such results as I have just noted, and with the ability to gather in a quarter of an hour observations which could not have been obtained with equal accuracy in years of former work, the problem of the solar constant and the absorption of the solar radiation within the solar envelope, and within the Earth's atmosphere, has, after long intermission, now been taken up again at the Smithsonian Astrophysical Observatory, not with the expectation that a final solution can be reached, in its unfavorable local conditions, but with the hope that we may reach a useful approximate one, and become

familiar in practice here with methods to be carried out later, it is hoped, under more favorable conditions.

4. *The method of study.*—The work now commenced here is planned to include the following parts:

a) A study of the yearly variations of the selective absorption of the Earth's atmosphere by the aid of a long series of bolographs.

b) The production of bolographic energy spectrum curves at different altitudes of the Sun for the purpose of obtaining coefficients of atmospheric transmission at any desired wave-lengths.

c) Experiments to determine the loss experienced by the radiations in passing through the various optical parts of the bolographic apparatus.

d) The standardization of the bolographic apparatus by actinometer observations simultaneous with the bolographs.

e) The reduction of these several kinds of data to furnish coefficients of atmospheric transmission, coefficients of transmission of the apparatus, and ultimately means of getting values of the solar constant.

These five classes of studies refer mostly to absorptions within the Earth's atmosphere, but finally, and of the greatest importance to the immediate study of the variations of solar radiation, comes a study of the absorption of the solar envelope for any desired wave-lengths by means of bolographs taken at selected points on a large solar image.

5. *Selective absorption of water vapor.*—Continuing our consideration of the absorptions in the Earth's atmosphere, we observe that this chart (Plate VIII) gives a summary of eight months of bolographic spectral actinometry. The bolographs taken near noon of all clear days since February, 1902, have been reduced to a uniform scale of ordinates by a method which need not here be described, and their areas between wave-lengths 0.76μ and 2.0μ have been obtained. These areas are proportional to the total solar radiation between wave-lengths 0.76μ and 2μ which reaches the sea level.

In this infra-red portion occur the great water vapor absorption bands $\rho\sigma\tau$, ϕ, ψ, and Ω, but there is some reason to suppose that the percentage absorption of water vapor is no greater here than in the visible spectrum as a whole.

The areas measured are plotted in the upper curve of Plate VIII. It will be seen how broken and variable the height is, but how the general slope indicates a considerable falling off in energy in the summer months. The reason of this appears in the next lower curves. Of these the dotted one gives the summation of the areas of those parts of the bolographs known to suffer greatly from water vapor absorption, and the full one gives the remainder not so much affected by it. You see how obviously our solar radiation is affected by the water vapor in the air. The difference between March and August amounts to about 20 per cent. It has been pointed out in Vol. I of the *Smithsonian Astrophysical Observatory Annals* that this water vapor absorption is annually periodic in its fluctuations, and is at a minimum in spring. A secondary minimum occurs in the autumn.

6. *The general absorption of the Earth's atmosphere.*— During the past year attempts have been made on each promising day to get a series of solar energy curves taken with different altitudes of the Sun, beginning in the morning and continuing every hour till late in the afternoon. Many of these series were stopped or rendered valueless by the appearance of clouds or haziness; for it is, indeed, surprising to find how little apparent change in the clearness of the air alters decidedly its transparency for some wave-lengths.

The method of reduction of the observations is as follows: A number of points on the bolographs are selected where there are no prominent bands of selective atmospheric absorption. At these points the heights are proportional to the deflections of the galvanometer and to the amounts of solar radiation of certain known wave-lengths which fall upon the bolometer. For each bolograph the time of passing these selected points is known, and therefore the altitude of the Sun.

We thus have all the data for fixing the mass of air traversed by the solar beam on several occasions, and the relative amounts of radiation of certain wave-lengths remaining after the passage through the air column. We assume now the validity of the familiar formula of Bouguer, which seems, as applied to individual wave-lengths, to express well the results of these experiments.[1]

Such a procedure as I have indicated, applied to the work of six of the best days, has yielded the results which appear on this chart (Plate IX) before you. The six thin broken lines show the values of atmospheric transmission coefficients determined for the twelve different wave-lengths as indicated by the abscissæ of the chart. The heavy line represents the mean result of these six different days of observation. You will see how well the results generally agree. They were taken from different seasons of the year and very different air masses. The significant depression of the curve as it ends in the infra-red and also near the D lines I suppose to be due to a general absorption of water vapor in these spectral regions.

Another interesting feature of the work is that in the morning hours the transparency of the air generally increases rapidly and sometimes irregularly, while in the afternoon it continues longer of nearly uniform and maximum transparency. This result is shown by this chart (Plate X), in which the lines are plotted from the values of log d and $m\frac{B}{B_0}$ (see footnote, p. 95)

---

[1] If we suppose e to represent the amount of radiant energy per square centimeter of the given wave-length which reaches the Earth's surface; e_0 the amount prior to absorption by the air; a the proportion transmitted by a unit air mass, represented by vertical transmission through an air column of barometric pressure B_0, then for the given barometric pressure B and for the air mass m we have by Bouguer's formula:

$$e = e_0 a^{m\frac{B}{B_0}} .$$

But since the height of the bolograph d at the given wave-length is proportional to e, we may write, by introducing an instrumental constant k,

$$d = ke = ke_0 a^{m\frac{B}{B_0}} .$$

It is convenient for graphical computation to put this formula in logarithmic form as follows:

$$\log d = m\frac{B}{B_0}\log a + \log ke_0 .$$

The last member of this equation is supposedly constant, and hence we have here the equation of a straight line. Accordingly, if all the observed values of log d and $m\frac{B}{B_0}$ are plotted on any convenient scale, the quantity log a appears as the tangent of the inclination of the line determined by them.

for two different days at a wave-length of 0.51μ. As I have said, all the observed points should lie upon a straight line the tangent of whose inclination is the value of log a. It will be noted that the morning hours yield much steeper and more irregular lines than the afternoon hours, indicating the increase of transparency, which culminates shortly after noon.[1]

This general result of the preliminary experiments on the Earth's atmosphere may be of interest to meteorologists.

7. *The absorption of the apparatus and its standardization by the actinometer measures.*—Let us recall that before reaching the bolometer each ray of light, of whatever wave-length, is diminished in intensity, first by the absorption of the solar envelope, second by the absorption and diffuse reflection of the Earth's atmosphere, third by a similar loss at the siderostat mirror, and fourth within the spectroscopic train. These several losses are not the same for different wave-lengths, but all tend to increase as we pass from the infra-red into and through the visible spectrum.

The atmospheric transmission has just been mentioned, and we will now consider the losses within the train of apparatus. In my earlier work at Allegheny, I determined the reflection coefficients for silvered glass mirrors, and more recently other investigators have done the same. I do not therefore stop to give more recent results obtained here, as they are in substantial agreement with these others, but it may be well to say that, inasmuch as the reflecting power of the silvered siderostat mirror rapidly deteriorates in the visible spectrum, it is necessary to determine this quantity frequently in solar constant work.

Similarly, the three mirrors of the spectroscope deteriorate, and require that frequent determinations of the relative transmission of the spectro-bolometer for all wave-lengths should be made. I do not here detail the elaborate procedure adopted for this purpose.

Referring to Plate VII again, you see before you five solar

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[1] It is at the same time to be noted that conditions of "good seeing" are usually associated with the morning hours.

spectrum energy curves. Take any one of these in illustration. Its ordinates represent intensities of radiation for all wave-lengths from 0.45μ to 2.5μ. The area bounded by this curve and the axis of abscissæ is therefore proportional to the total solar radiation between these wave-lengths which reaches the bolometer. If now all the ordinates should be increased by dividing their lengths by the corresponding transmission coefficients of the spectro-bolometer, we should obtain a new corrected energy curve. This curve may be extended by extrapolation to include the small amounts of solar radiation not included between wave-lengths 0.45μ and 2.5μ,[1] and its area will then be proportional to the total solar radiation in the beam reflected by the siderostat mirror.

8. *A provisional value of the solar constant.*—In the steps which follow, the necessary data are introduced to furnish a provisional value of the solar constant.

The energy curve is corrected for the loss at the siderostat mirror, and further, by the application of Bouguer's formula and the atmospheric transmission coefficients, the form of the energy curve outside the Earth's atmosphere is reached. Before this final step all the great terrestrial bands are smoothed over. Plate XI illustrates the several steps by means of which the bolograph is corrected to exhibit the distribution of the solar energy outside the Earth's atmosphere. Curve (1) is the bolograph itself. Curve (2) is corrected for relative absorption in the spectroscope. This curve is extended at either end to include what may reasonably be estimated as the solar radiation beyond its limits. The shaded area under curve (2) represents an actinometer reading of 1.36 calories per square centimeter per minute.

Curves (3) and (4) give the distribution of the solar radiation in the prismatic spectrum respectively at the Earth's surface and outside the atmosphere. The area under curve (4) is 1.87 times the area under curve (2), and we therefore find from this

---

[1] In a more exact determination of the solar constant these amounts would require careful measurement, but in this illustration only a rough extrapolation is attempted.

single determination that the solar constant is 2.54 calories per square centimeter per minute.

(The reader will understand that this is but a provisional value, given to illustrate the method, which, it is hoped, may be pursued later under more favorable local conditions. It is, indeed, unlikely that even by much greater labor we can obtain an accurate value of the constant from a station so near sea level as Washington, where the atmospheric absorption is so large and doubtful a factor. It will be remembered also that the writer has elsewhere shown that such values obtained near sea level are always of necessity too small.)

I cannot leave this part of the subject without acknowledging my constant obligation to my assistants, Mr. C. G. Abbot and Mr. F. E. Fowle, for aid in every part of the work.

We now reach the most important part of our study of the so-called solar constant, and of its possible variation.

9. *General absorption of the solar envelope.*—A chief cause of possible variability of the solar radiation is in the solar envelope itself. The absorption of this envelope may well be variable, as I have remarked in earlier articles,[1] in which I have indicated how far the surface temperature of our planet may depend upon it, and Halm has recently[2] put forth an ingenious theory to explain the Sun-spot cycle on this basis. I refer to this now only to point out that bolometric work upon the direct solar image and on the relative amounts of radiation of all wavelengths, and from its various parts formerly carried on by me elsewhere, has been now taken up at the Smithsonian Observatory, and that a description of it will probably form the subject of a later memoir. Inasmuch as we receive heat and light through different thicknesses of the solar envelope at different parts of the disk, we have here, with the thermal study of faculæ, prominences, and spots, a means of studying solar absorption and radiation which, if continued (as I hope it may be) over a Sun-spot cycle, will determine our knowledge of whether the Sun's radiations to the Earth vary, as I am disposed to believe, from month to month and year to year; and which may, it seems

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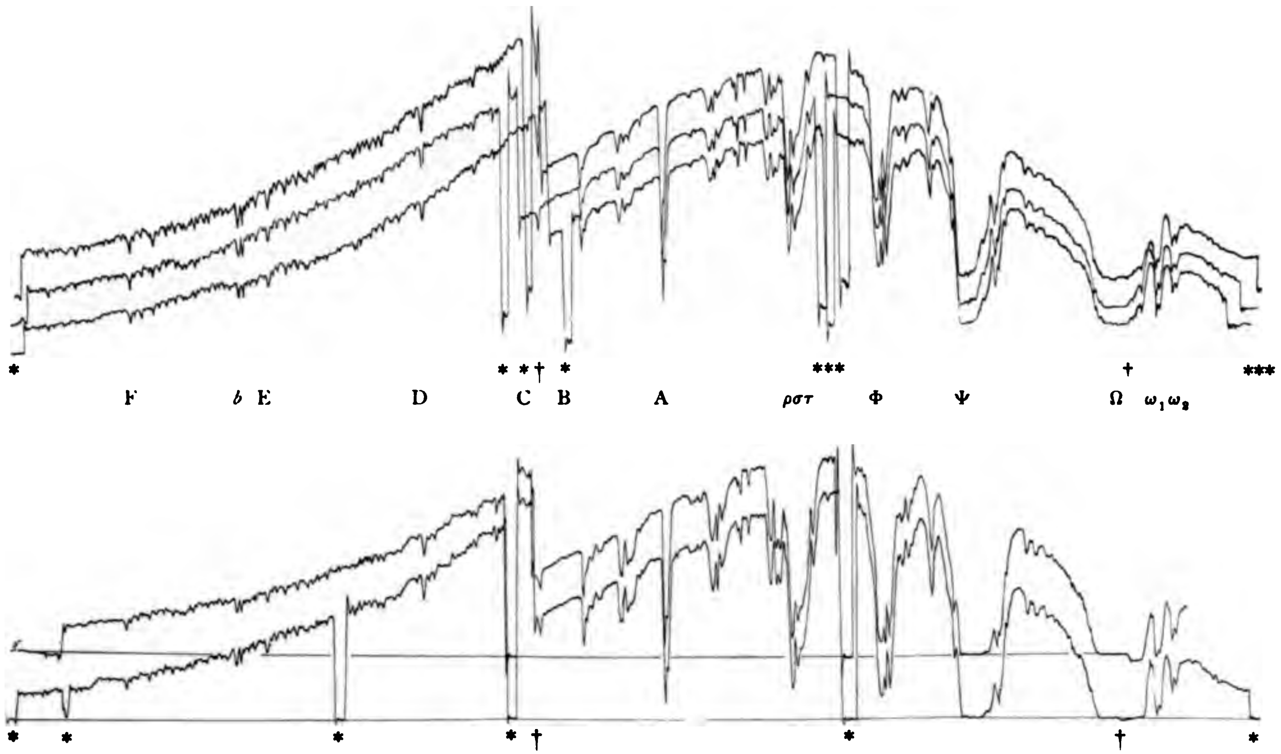
[1] *Am. Jour. Sci.*, 10, 489, 1875.

[2] *Nature*, February 13, 1902.

PLATE VII.

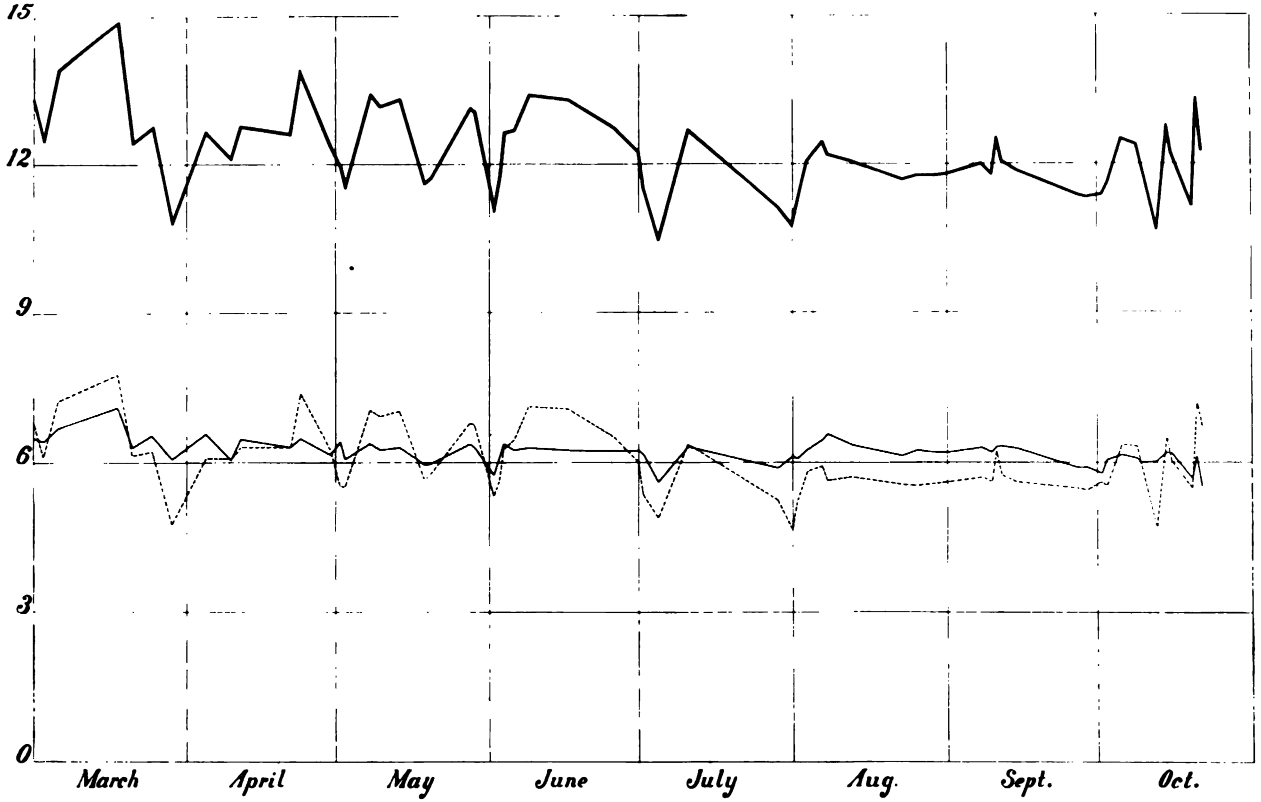


Bolographic Energy Curves of the Prismatic Solar Spectrum.

Each curve made in fifteen minutes. The three upper curves taken on a day of moderate water vapor absorption; the two lower curves indicate much greater absorption. See bands *ρστ*, Φ, Ψ.

*** Shutter closed at these points to give zero line.** **† Height of slit altered at these points.**

PLATE VIII.

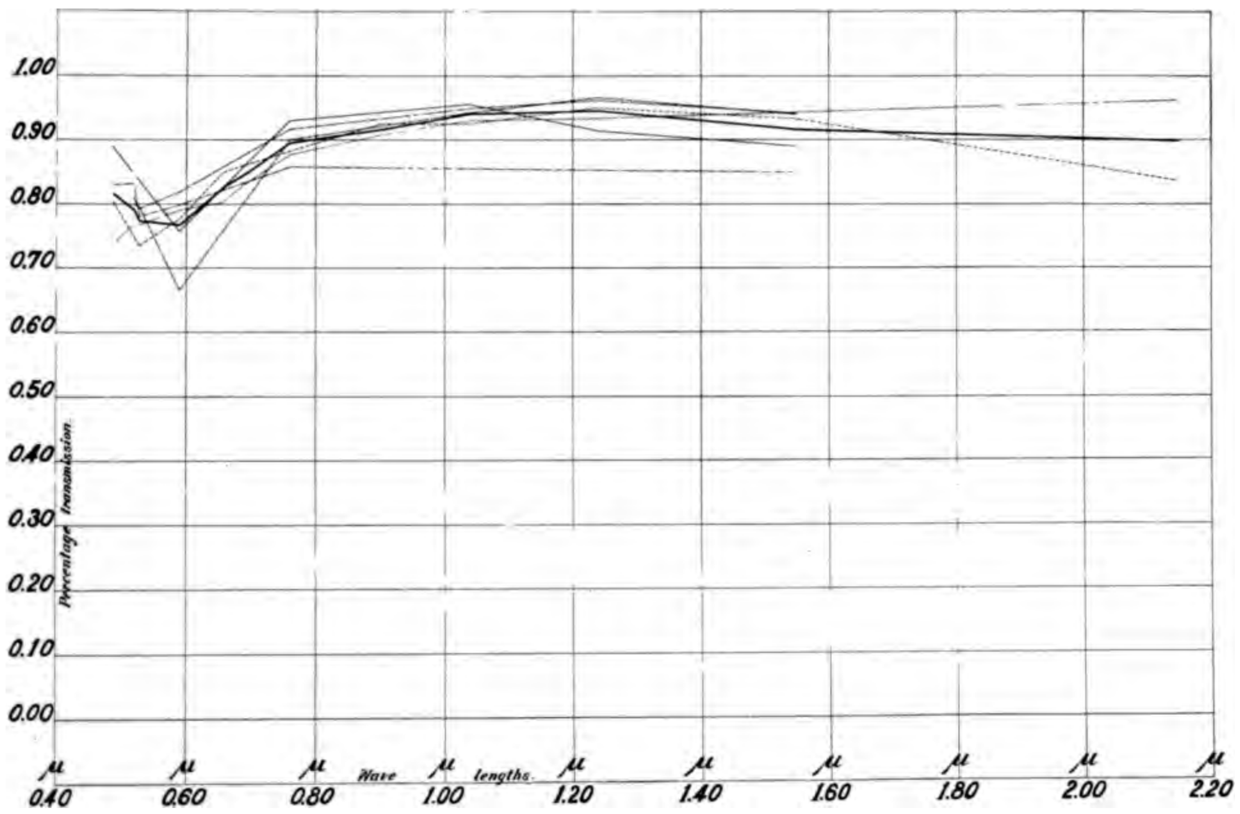


Variation of Solar Radiation Caused by Differences of Atmospheric Absorption.

(From Bolographic Studies of 1902.)

Upper curve represents total radiation between wave-lengths 0.76 μ and 2.0 μ.
Dotted curve represents portion of this affected by the great water absorption bands.
Lower full curve represents the remainder relatively unaffected by absorption of water vapor.

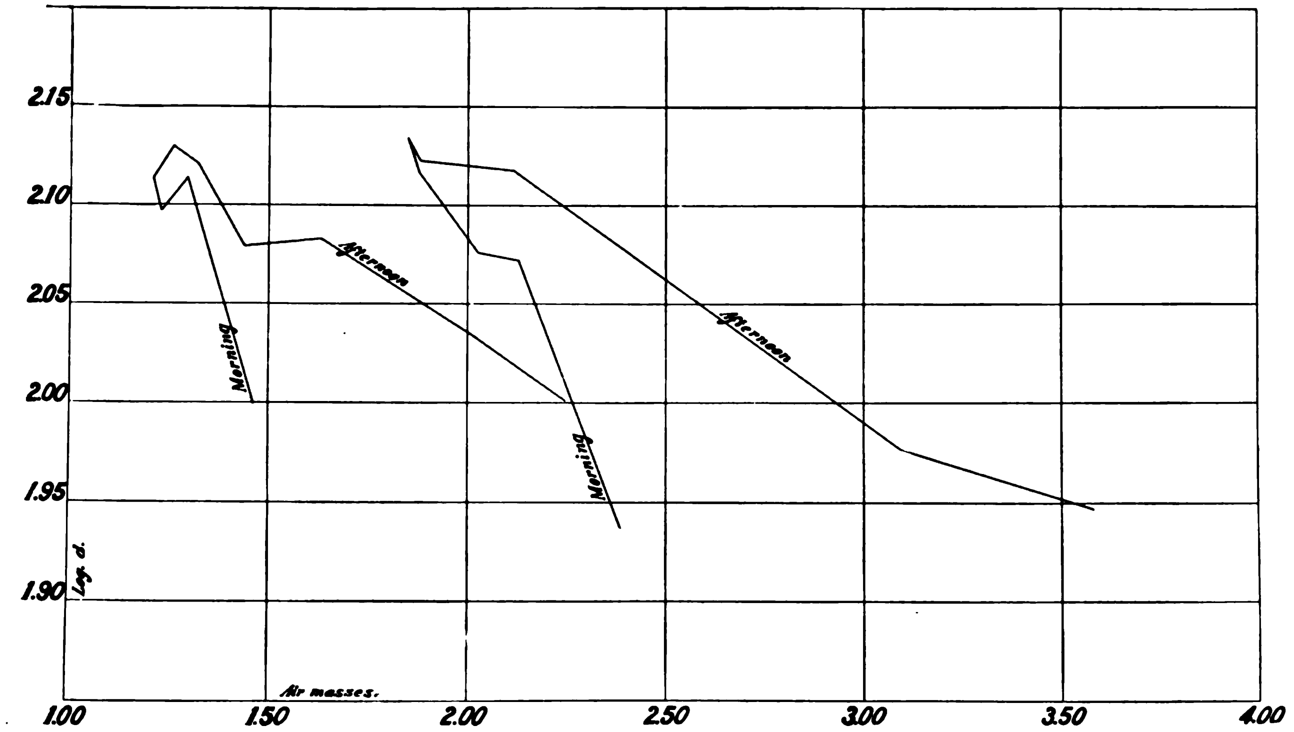
PLATE IX.



TRANSMISSION OF EARTH'S ATMOSPHERE AT WASHINGTON FOR VERTICAL AIR COLUMN AT 76 CM BAROMETRIC PRESSURE.

The heavy line is the mean of the results of six afternoons' bolographic observations.

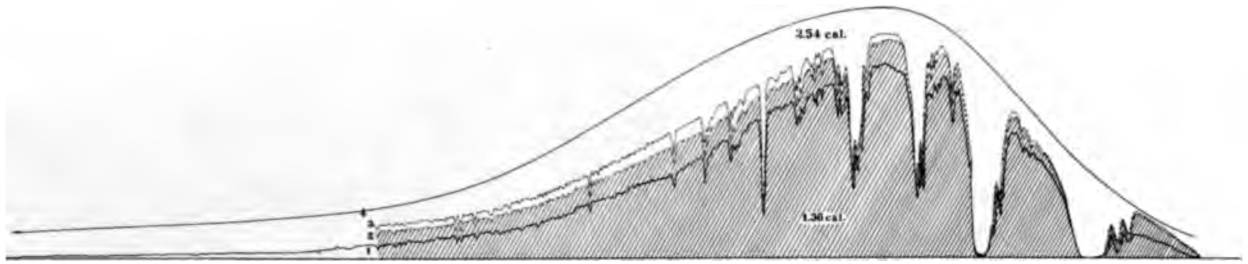
PLATE X.



VARIATION OF ATMOSPHERIC TRANSMISSION AT WASHINGTON FOR MORNING AND AFTERNOON HOURS.

The observations are for wave-length 0.51 μ and for two different good days. If the transparency of the atmosphere remained uniform, all the points plotted for each day should lie upon a straight line, the tangent of whose inclination is log *a* of Bouguer's formula.

PLATE XI.



Bolographic Method of Determining the Solar Radiation Constant.

Curve 1 is the original bolograph.
Curve 2, same corrected for absorption of spectroscope, and representing by its shaded area a known actinometer reading.
Curve 3, same corrected for absorption of siderostat mirror.
Curve 4, same corrected for absorption of Earth's atmosphere.

increasingly probable, ultimately bring to light evidence of variation in the heat it sends to the Earth, which may not only interest the astronomer, but be of practical consequence to all men.

SUPPLEMENTARY.

Need of an elevated solar observatory.—The Earth's temperature and the life of its inhabitants, both animal and vegetable, depend on the solar radiation. Yet we confess that even at this late day we do not know, with any certainty, what the total amount of solar radiation is, whether it is constant or variable, or what effect upon terrestrial life and temperature a given change in it would produce. Our ignorance of these fundamental things is largely, though not wholly, due to the variability of our own atmosphere, which prevents us from studying that of the Sun.

The preceding observations are carried on here with extreme difficulty under the almost prohibitive local conditions for such work. We must at least attempt a determination of the solar radiation, and its possible variation under these conditions; although what is more urgently needed, as I believe, than any other desideratum of physical astronomy, is to establish an observatory, placed in some clear and elevated region and charged solely with problems relating to the possible variations of the heat the Earth receives from the Sun. I have referred to the former expedition to Mount Whitney for this purpose, but it is not a temporary expedition, but many years' occupation which is now in question. Now that great undertakings are the order of the day, let us hope that some way may open to reach the solution of a problem which so concerns the whole human race.

SMITHSONIAN INSTITUTION,
Washington, D. C., February 7, 1903.

ON THE OPTICAL CONDITIONS REQUIRED TO SECURE MAXIMUM ACCURACY OF MEASUREMENT IN THE USE OF THE TELESCOPE AND SPECTROSCOPE.

By F. L. O. WADSWORTH.

(*Concluded from p. 19, Vol. 17, January 1903.*)

The effect of curvature of the prism faces or of varying optical density in the material of which they are made has already been investigated in part for plane wave-fronts (Vol. **16**, pp. 289–294). So far as this effect is individually considered it will be practically the same with spherical wave-fronts of small curvature as with plane wave-fronts, but it may happen that in the case of spherical wave-fronts the unsymmetrical aberration due to either or both of these causes may be in the same direction as that due to the prism train itself, or it may be in the opposite direction. In the first case the two effects are additive and the amount of permissible aberration due to each is correspondingly reduced, *i. e.*, for a given error of setting of the slit the amount of permissible temperature variation in the prism train is less than that indicated in (42),(44) and (45) by an amount depending on the sphericity of the incident wave-front. In the latter case the effects are to a certain degree compensatory, but, on account of the different form of distortion given to the wave-front by the two causes, the compensation can be exact only under certain conditions. Thus in the case of a single prism, which has also been investigated by Lord Rayleigh,[1] it is found that the aberration due to sphericity of the incident wave-front and the aberration due to curvature of the prism faces can destroy each other only when the curvature of the two faces is in opposite directions (*i. e.*, one face convex and the other face concave) and very nearly equal. In the case of varying optical density it is necessary to secure compensation to have at least two prisms in the train whose variations are in opposite directions.

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[1] *Phil. Mag.*, 9, 46–48.

From these general considerations it is evident without further investigation that, so far as the limiting aberration in the beam emerging from the spectroscope train is concerned, we cannot rely upon compensatory effects in enabling us to reduce the rigor of the conditions already imposed in (42) and (66), since any one or all of the effects involved are liable to change in amount, and even in sign with changes of temperature. The best that we can do in any case is to so adjust the focus of the collimator and the order of succession in the prism train, that under what might be termed normal conditions of temperature and adjustment the wave-front issuing from the final prism face at minimum deviation is most nearly plane; or, in other words, to determine by one of the methods which will be mentioned later the accurate focal length of the collimator and prism train *combined*, not of the collimator alone as usually done, and then to set the slit as indicated on pp. 17 and 18.

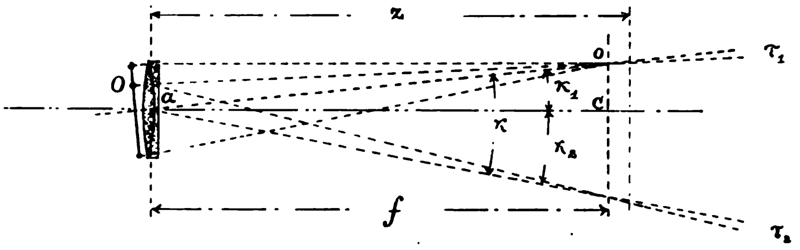

FIG. 11.

When the incident wave-front is not symmetrical with reference to the axis of the instrument, the displacement of the image of a point or line due to a change in focus will depend on the distribution in intensity in the diffraction image in planes outside the principal focal plane. The detailed investigation of this problem in the case of a beam affected by unsymmetrical aberration or eccentrical incidence is a matter of considerable complexity. In the present case we may assume that for small distances *df* from the true focal plane the center of intensity of the diffraction pattern will lie on a line which passes through the central point, *o*, of the image at the principal focus, and the point O, which marks what may be termed the mean center of illumination of the incident wave-front. Let the angle between this line oO, and the secondary optical axis, oa, *i. e.*, the angle aoO, be τ. Then if the angle oac be κ as before, it is evident that the distance ξ, of an image from the central point c of the plane in which it lies, will be

$$\xi_1 = f \sin \kappa_1 + (z - f) \sin (\kappa_1 - \tau_1) \ . \tag{95}$$

The separation of two images which lie at equal distances on opposite sides of the optical axis and having a total angular separation κ will be

$$\xi = 2\xi_1 = f \sin \kappa + (z - f) \left\{ \sin \left(\frac{\kappa}{2} - \tau_1 \right) + \sin \left(\frac{\kappa}{2} + \tau_2 \right) \right\} ,$$

or since κ and τ_1, τ_2 are all very small angles

$$\xi = z \{ \kappa - (\tau_1 - \tau_2) \} + f (\tau_1 - \tau_2) \tag{96}$$

and

$$\left. \begin{aligned} d\xi &= dz \{ \kappa - (\tau_1 - \tau_2) \} + df (\tau_1 - \tau_2) \\ &= \frac{dz}{f} (\xi - S) + \frac{df}{f} S \end{aligned} \right\} , \tag{97}$$

where S is, as before, the total linear separation of the mean centers of illumination of the incident wave-fronts.

Comparing (97) with (58) we see that in this latter case the change in the separation of the two images involves the consideration of the change in both z and f. It is necessary therefore to know the law of variation of f with t to the same degree of exactness as that with which we know the coefficients of linear expansion α, α', and α'' involved in a change in z.

Expressing the values of dz and df in the same form as before [(63) and (94)], and taking into account the expansions of the micrometer screw and photographic plate, etc., as in (59) and (60), we finally obtain in this case:

First, for direct micrometric or heliometric measurements at the focal plane $f \cong z + d\Omega$,

$$\begin{aligned} \Delta\xi = \kappa (z + d\Omega) (\alpha - \alpha') \Delta t + d\Omega \left[\kappa - (\tau_1 - \tau_2) \right] \\ - (\tau_1 - \tau_2) (z + d\Omega) (\alpha - \alpha''') \Delta t \ , \end{aligned} \tag{98}$$

and second, for comparator measurements on photographic plates

$$\begin{aligned}\sum_{t}^{T}\xi &= \kappa(z + d\Omega)\left[(a - a')\,\Delta t + (a' - a'')\,\Delta' t\right] \\ &\quad + d\Omega\left[\kappa - (\tau_1 - \tau_2)\right] - (\tau_1 - \tau_2)(z + d\Omega)(a - a''')\,\Delta t \;. \qquad (99)\end{aligned}$$

When $\tau_1 = \tau_2$, *i. e.*, when the mean centers of illumination S_1 and S_2 are incident at the same point on the objective, the measured separation between any two images is exactly the same in the case of eccentrical incidence as in the case of centrical incidence (64) and (65), previously considered. From this it follows that any unsymmetrical diaphragming or unsymmetrical absorption (the effect of which is the same) is without effect on $\Delta\xi$, provided only that the wave-fronts in each case fill the whole aperture. The position of each individual image, however, will be shifted by an amount indicated by differentiating (95), and the application of this principle forms the basis of the ingenious methods that have been described by Cornu,[1] Newall,[2] Hartmann,[3] and others for determining the exact focal length of a telescope.

If the focusing were always exact we would have

$$\begin{aligned} d\Omega &= (a - a''')\,f\Delta t \\ &\cong (a - a''')(z + d\Omega)\,\Delta t \;, \end{aligned} \qquad (100)$$

and under such circumstances (98) and (99) would again reduce to forms identical with (64) and (65). Exact focusing, in the sense in which the term is used in metrological work, is, however, never possible by the ordinary standards of definition; hence it is better to consider these terms separately.

The quantities a, a', a'', and a''', which appear in the first and last terms of (98) and (99) are all small and may be accurately determined once for all. Hence since $d\Omega$ is always small compared to z, and κ is known from the measurements themselves, we can, as we have already shown, determine the value of the first term of these corrections with all requisite accuracy if we know the value of Δt within 3° (± 1°.6). In order to do the same for the other two terms we must first of all determine the values of the angles τ_1 and τ_2.

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[1] *Ann. de l'École Normale*, (2) 9, 21.

[2] *M. N.*, 57, 572, 1897.

[3] ASTROPHYSICAL JOURNAL, 12, 37, 1900.

The first and most interesting case to be considered is that of the prism spectrograph. Here the separation of the axial pencils of the two extreme wave-fronts is produced by the dispersion of the spectroscope train. The amount of this separation has already been calculated [see equation (34)].

If there were no absorption in the prism train, and the prisms and view telescope had apertures sufficiently large to transmit the entire beam of the two extreme lateral pencils, the separation S given by (34) would be that required in (97). Owing to the unsymmetrical absorption, however, the mean center of illumination O will not be on the axis of the wave-front, but will be displaced toward the refracting edge of the prism by an amount proportional to the coefficient of absorption. With the same notation as that already employed in (8) and (9) we have for the total quantity of light transmitted

$$\begin{aligned} A &= \int_{-\frac{b}{2}}^{+\frac{b}{2}} i_0 e^{-Bx}\,dx \\ &= \frac{i_0}{B}\left[e^{\frac{Bb}{2}} - e^{-\frac{Bb}{2}}\right] . \end{aligned} \tag{101}$$

Hence the mean center of illumination O will lie at a point S_0 such that

$$i_0 \int_{-S_0}^{\frac{b}{2}} e^{-Bx}\,dx = \frac{1}{2} A , \tag{102}$$

which by comparison with (101) gives at once

$$S_0 = -\frac{1}{B} \text{nap log} \frac{e^{\frac{Bb}{2}} + e^{-\frac{Bb}{2}}}{2} . \tag{103}$$

For $B = \frac{1.386}{b}$, as previously assumed,

$$S_0 \cong -\frac{1}{6} b , \tag{104}$$

and therefore

$$\tau_1 = \frac{S_0}{f} \cong -\frac{1}{3} \beta ,$$

i. e., the center of illumination is displaced one-sixth the entire diameter of the wave-front toward the refracting edge of the prism train, and the angle τ_1 for the wave-front passing at minimum deviation is one-third the semi-angular aperture of the view telescope.

In order to avoid displacement of the central image (for which $\kappa = 0$) with change of focus, the center of the objective must coincide with the mean center of illumination O; *i. e.*, the principal axis of the view telescope should not lie on the axial line of the ray transmitted at minimum deviation but should be shifted toward the refracting edge of the prism train by the amount indicated in (103). This is a point generally overlooked in the design of spectrographs.

In the case of lateral pencils the value of the middle term representing the effect of the mechanical change in focus will be less or greater according as the signs of τ_1 and τ_2 are the same or opposite, and according as the sign of their differences is the same or opposite to the sign of κ. If τ_1 has the same sign as κ we may make the term $\kappa - (\tau_1 - \tau_2)$ zero by properly controlling S_1 and S_2, the points of incidence of the centers of illumination of the lateral wave-fronts. In the case of the spectrograph this can be accomplished by so proportioning f, the focal length of the view telescope, and L, the total length of path through the prism train, that the value of S in (97) and (34) is identical with the value of ξ, the separation of the two images at the focal plane. This gives us, from (34) and (35),

$$f(\tau_1 - \tau_2) = f\kappa = \frac{d\theta}{d\lambda}\left[\frac{1}{2}\left\{ L_1 + 3L_2 + 5L_3 + \cdots\cdot (2N-1)\,L_N \right\} + n\left\{ L_1 + 2L_2 + 3L_3 + \cdots\cdot N\frac{L_N}{2} \right\}\right], \qquad (105)$$

or since the total angular displacement κ is $2N$ times the displacement $\frac{d\theta}{d\lambda}$ for one refraction, we have for three prisms

$$f = \frac{1}{12}\left[L_1 + 3L_2 + 5L_3\right] + \frac{1}{6}n\left[L_1 + 2L_2 + 3\frac{L_3}{2}\right]. \qquad (106)$$

For the Bruce spectrograph already considered

$$f = 10.08 + 16.42 = 26.5\ \text{cm},$$

instead of 44.9 cm and 60.7 cm, as adopted for camera A and camera B.

Since (34) is deduced on the assumption that the prisms and objective of the view telescope are placed as close together as possible, (105) and (106) express the minimum value of f that will satisfy the above condition for the elimination of the term $\kappa - (\tau_1 - \tau_2)$. We can, however, satisfy this condition for any *larger* value of f by separating the prisms or by withdrawing the camera objective so that the total path L through the spectroscope train is correspondingly increased. It is so easy to do this in the original design of the instrument, and the advantage resulting from it in the entire elimination of the effect of errors in the scale reading Ω is so great, that it is singular that this particular point of design seems to have been previously overlooked.

We may accomplish the same result in the case of the plane-grating spectrometer by making the distance from the grating to the objective of the view telescope equal to the focal length of the latter. In this case as before the objective of the view telescope must be increased in size sufficiently to receive the entire cross-section of the lateral beams. In this latter case the use for which the instrument is intended, as well as the form of view telescope adopted, must be considered before we can determine in any case whether it is worth while to introduce this modification of the usual design. With reflecting view telescopes the condition is very easily and almost necessarily satisfied, and this is another advantage of this form of grating spectroscope.[1]

In the case of the heliometer we may satisfy the same condition of zero displacement with change in the position of the eyepiece by proper diaphragming. With a full semi-circular aperture the total quantity of light in the transmitted wave-front is proportional to $\frac{1}{2}\pi r^2$. If we diaphragm one edge of the aperture by an amount mR the amount of light transmitted will be

$$\left.\begin{aligned} A &= \int_{-R}^{R(1-m)} \sqrt{R^2 - x^2}\, dx \\ &= \frac{R^2}{2}\left[(1-m)\sqrt{2m - m^2} + \sin^{-1}(1-m) + \frac{1}{2}\pi\right] \end{aligned}\right\} . \quad (107)$$

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[1] *Phil. Mag.*, 38, 137; ASTROPHYSICAL JOURNAL, 1, 232, etc.

The mean center of illumination of the diaphragmed aperture lies at a point S_0 such that $S_0 = R(1-n)$ and

$$\int_{-R}^{-R(1-n)} \sqrt{R^2 - x^2}\, dx = \frac{1}{2} A \ ,$$

and therefore

$$\left.\begin{aligned} &2\ [(n-1)\sqrt{2n-n^2} + \sin^{-1}(n-1)] + \frac{\pi}{2} \\ &= (1-m)\sqrt{2m-m^2} + \sin^{-1}(1-m) = \frac{2}{R^2}A - \frac{\pi}{2} \end{aligned}\right\} = A_m \ . \qquad (108)$$

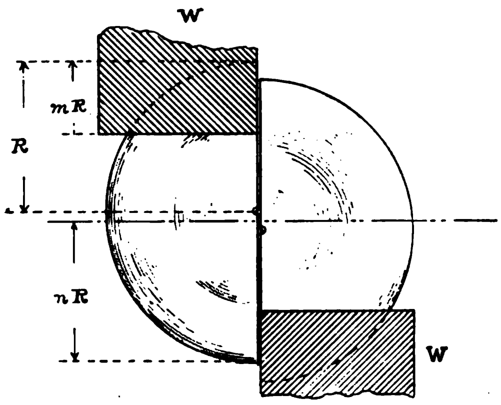

FIG. 12.

Let $A_0 = \frac{1}{2}\pi R^2$ be the amount of light transmitted when there is no diaphragm. Then we have from (107) and (108)

$$\frac{A}{A_0} = \frac{A_m}{\pi} + \frac{1}{2} \ . \qquad (109)$$

Equation (108) serves to determine m, the amount of diaphragming required for any given value of n, and (109) gives the ratio between the illumination secured with this diaphragm and the illumination with full (half) aperture. To determine n we have also in this case

$$S_0 = f\tau_1 = f\frac{\kappa}{2} = R(1-n) \ ,$$

whence

$$n = 1 - \frac{\kappa}{2\beta} \ . \qquad (110)$$

Assume as before that for a 16 cm heliometer $\beta \cong .03$. Then for two objects separated by an angular interval of 0°.5, $\frac{\kappa}{2} = 0.00436$ and $n \cong 0.855$, *i. e.*, the center of illumination of the incident wave-front should fall upon each half of the divided lens 0.145 of the radius from the center. This is accomplished by giving to m a value obtained by solving (108) for $n = 0.855$. We thus obtain

$$m = 0.475 \;,$$

i. e., a little less than one-fourth of each half of the objective should be covered, as in Fig. 12, the screens *W W* being placed so as to shut out in each case the light from the edge which is on the opposite side of the optical axis from the image formed by that half.

By expressing κ as a fractional part of β we can determine the general relation between κ and m for any heliometer. This has been done for values of $\frac{\kappa}{\beta}$ varying by tenths from 0 to 1 and by 0.2 from 1 to 2. The results for A_m, $\frac{A}{A_0}$, and m are given in Table IV and plotted in Fig. 13.

With this relation it is easy to devise a mechanical arrange-

TABLE IV.

$\frac{\kappa}{\beta}$	n	A_m	$\frac{A}{A_0}$	m
0	1.00	1.5708	1.00	0
0.1	0.95	1.3706	0.9363	0.230
0.2	.90	1.1726	.8732	.369
0.3	.85	0.9738	.8099	.490
0.4	.80	.7774	.7473	.600
0.5	.75	.5808	.6849	.705
0.6	.70	.3876	.6233	.805
0.7	.65	.1994	.5634	.900
0.8	.60	.0144	.5046	.988
0.808	.596	.0000	.5000	1.000
0.9	.55	− .1664	.4471	1.085
1.0	.50	− .3422	.3911	1.172
1.2	.40	− .6770	.2845	1.345
1.4	.30	− .9784	.1886	1.512
1.6	.20	−1.2424	.1047	1.678
1.8	.10	−1.4542	.0372	1.840
2.0	.00	−1.5708	.0000	2.000

ment which will automatically move the screens *W W* of Fig. 12 by the required amount when the two halves of the object-glass are adjusted to bring two images separated by the angular interval κ into coincidence. The great advantage of such an arrangement in the case of the heliometer is that when it is adopted the eyepiece may be moved in or out at will to suit the convenience and personality of the observer without thereby introducing any differences or errors in the settings of the instrument itself. The only drawback is that the light is considerably reduced for objects having considerable separation.

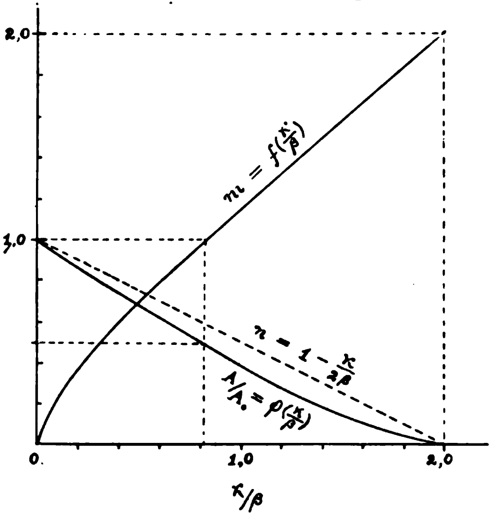

FIG. 13.

In this case, as in the preceding, the values of the angles τ_1 and τ_2, which appear in the third terms of (98) and (99), are determined by the relations

$$(\tau_1 - \tau_2) f = f(\kappa) ,$$

and these terms reduce to the form

$$\kappa f(a - a''') \Delta t , \qquad (111)$$

in which all the quantities are known or may be measured, and which, like the first terms of these equations, may be computed with all necessary accuracy when we know Δt for ordinary object-glasses to within about 3°. Temperatures of the object-glass and telescope-tube may be easily observed with this degree of accuracy, but we may by the special optical construction already mentioned on page 19 eliminate this term entirely by making $a - a''' = 0$.

B (3). It would be impossible and, in fact, quite unnecessary to enter here upon a general discussion of the methods of optical measurement best suited to individual cases. We shall endeavor to point out only some general principles of working which the previous investigations have shown that it is necessary to regard if we aim at the highest attainable degree of accuracy in our work, and to investigate in this connection one or two individual sources of error in the use of particular instruments which seem either to have escaped previous attention, or at least to have been considered less carefully than their importance demands.

In general, the causes will produce the maximum effects in the optical distortion and displacement of images, and the ones therefore which we must most carefully guard against are those dealt with in sections *A* (2), *A* (3), *B* (1), and *B* (2).

In order to eliminate, or minimize as far as possible, the effects of asymmetrical, spherical, or chromatic aberration, A (2) and A (3), we must employ instruments and methods of work planned with special reference to *avoiding* the following sources of error: (1) the use of too large fields or of too great angles of incidence, particularly when using short focus mirrors or gratings at the principal focus; (2) the use of methods of comparison or of forms of instruments and of optical construction which necessitates that the different images whose relative positions are to be measured are formed by different portions of the surfaces of the optical train; (3) variations in temperature conditions during the interval of measurement or of record; (4) the effect of small chromatic dispersions, particularly when the spectral curve of radiation is different for the different sources; (5) the effect of varying chromatic absorption and unsymmetrical broadening of the spectral lines when the chromatic dispersion is large.

In the case of errors of Class B we must especially guard against (6) the use of too small resolving powers, and (7) the continued effect of temperature variations and asymmetrical illuminations.

Of these various effects those which have heretofore received most attention are (3) and (7). Temperature variations are. indeed, our greatest source of trouble and error in the great majority of physical measurements of all kinds. It appears, however, from the results of the investigations on this point (pp. 292–4), that these effects are of even larger order of magnitude than is ordinarily assumed, and that in spectroscopic work particularly we must guard against them with the greatest care. As was pointed out on pp. 278, 279 and 292–4, the best method of eliminating residual effects, after reducing the temperature variations to the smallest possible range, is to measure the separation of the images and determine the so-called constants of the instrument, *i. e.*, focal length, pitch of measuring screw or scale, etc., simultaneously with each observation, instead of relying on values determined once for all at considerable intervals, as is usually done.

This method of simultaneous record is carried out most completely at present in determining star places by the chart photographs of the Astrophotographic Survey, in which the constants of reduction for each plate are determined from the photographic record on the plate itself. The next best example is that of the spectrographic method of determining absolute wavelengths and motions in the line of sight by the use of comparison spectra. The only criticism to the present practice of the method in the latter case is that the record of the comparison spectrum and of the spectrum to be measured is not simultaneous, and in the case of star spectra, in which an interval of sometimes two hours intervenes between the records, the residual errors of intermediate temperature variations, small though they may be, are in certain cases quite sensible. It would be much better, as already pointed out, if the exposure on the comparison spectra were made continuously instead of intermittently at the beginning and end of the exposure, and this could be arranged without any great difficulty.

It must be farther noted, however, that this method of simultaneous record and individual reduction of each set of measures, although it may eliminate almost completely the effect of small temperature variations, will not eliminate the effects of (1), of (2), of (4), of (5), nor of the latter part of (7), unless, indeed, the conditions of observation are precisely the same in all of these respects for both the objects upon which the direct measurements are made and the objects upon which the comparison measurements for the "constants" of reduction are executed. It is physically impossible always to fulfill this requirement in the case of (4) and (5), and frequently very difficult in the case of (1), (2), and (6) because of the different parts of the field in which the two sets of images (direct and comparison) are situated, or because of necessary limitations in the size and power of the observing instrument.

For these reasons it is unsafe, if we aim at the highest degree of accuracy in optical measurements, to neglect the causes of optical displacement considered above, or to assume beforehand that their effects are vanishingly small. In this connection it is necessary to insist again on the point already made, that the ordinary tests and standards of optical definition are not sufficiently rigorous to serve as criteria in determining questions relating to the limiting accuracy of measurement. Nor are we safe in considering our results free from constant errors which may arise from instrumental causes, simply because they agree consistently among themselves, or are checked by occasional measurements of known quantities. Our only safe way of procedure would seem to be to investigate in each individual case, as we have already done in the general one, the *maximum individual* effects produced by possible disturbances of theoretical conditions, and either to reduce each of these maximum individual effects (unless there may be two or more which are *always necessarily* compensatory) to a quantity less than ϵ, the limiting metrological power; or to determine the magnitude of each effect to the same degree of exactness, in order that it may be taken care of as a known correction. In such individual cases there may exist possible causes of disturbance of a special character not included in the general classes of errors already discussed. As stated at the beginning of this section, it is unnecessary and undesirable to take up in detail a complete discussion of any number of such cases.

There is, however, one individual case in which an error of measurement due to a cause not yet considered is very likely to be introduced, and which on account of its importance in one of the leading fields of astrophysical research we will consider at length. This is the case of the slit spectroscope or spectrograph as used for determinations of velocity of motions in the line of sight, or more generally of absolute wave-lengths. Here, in order either to secure greater intensity of spectrum, or to localize determinations with reference to different parts of the sources under examination, images of both the latter and of the comparison sources are first formed on the slit of the instrument, and we measure the relative positions, not of the spectral images of the sources themselves, as they would be formed by an objective prism or grating, but the relative positions of the spectral images of the slit as illuminated by the light concentrated upon it by the image-forming objective. The distinction is an important one, for, as we have seen in the case of A (3), any asymmetrical distribution in intensity in the source of radiation will result in an asymmetrical distribution in intensity in the image, and a consequent displacement of its center of maximum brightness. Hence if the slit is *not* uniformly illuminated across its entire width, its spectral image corresponding to any particular wave-length in the light falling upon it will be displaced from the position it would occupy under conditions of uniform illumination, no matter what the conditions in the source itself may be. The asymmetrical illumination of the slit may arise from (1) asymmetrical distribution of intensity in the image of the source itself on the slit, due either to a real asymmetry of radiation or to asymmetrical distortion or aberration of the image-forming objective; (2) displacements of the center of symmetry of the image with reference to the center of the slit. As the effect on the measurements will be the same in both cases we may consider them jointly.[1]

The general expression for the distribution in intensity in the

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[1] This effect is entirely different in nature from that produced by lack of uniform illumination of the collimator objective, which has already been considered in *B* (2). So far as I have been able to ascertain, the effect of asymmetrical illumination of the slit itself it had escaped attention previous to the time when the preliminary results of this paper were informally announced at the Astrophysical Conference at the Yerkes Observatory in 1897. It was then expected that these results would be at once investigated in detail by others more directly interested than the writer in line of sight work, but their bearing on this line of research seems to have been overlooked or not fully realized by those present at that time.

spectral image of a slit *uniformly* illuminated across its entire width by radiation from any individual spectral line has already been given [equation (52)], and this expression has been evaluated for a number of special cases.[1] If the illumination across the width σ is not uniform, we must add another factor, $f(\xi)$, to express this variation in intensity, which gives us in (52)

$$I_{,,,}=A''\int_{-\frac{\sigma}{2}}^{+\frac{\sigma}{2}} f(\xi)\,\psi_1\{\xi-\psi,\ a_0 a\}\,d\xi\ . \tag{112}$$

As in the consideration of a uniformly illuminated slit, we will first examine the case in which the light on the slit is absolutely monochromatic and the spectroscope itself is free from aberration. Then at the focal plane of the instrument the function ψ_1 becomes simply

$$\frac{\sin^2\frac{\pi a}{a_0}}{\left(\frac{\pi a}{a_0}\right)^2}\ ,$$

and we have for I,,,

$$I_{,,,}=A''\int_{-\frac{\sigma}{2}}^{+\frac{\sigma}{2}} f(\xi)\,\frac{\sin^2\frac{\pi}{a_0}(a-\xi)}{\frac{\pi}{a_0}(a-\xi)}\,d\xi\ , \tag{113}$$

which is the same form as that expressing the distribution in intensity in the image of an individual spectral line [equation (51)], for an infinitely narrow slit.

It is evident that (113) like (51) will be symmetrical or asymmetrical according to the form of the function $f(\xi)$. We will examine a few cases of particular interest in detail.

First, suppose

$$f(\xi)=A+B\xi\ . \tag{114}$$

This represents a uniformly progressive increase in the intensity of illumination across the entire width of the slit, such as is graphically illustrated in Fig. 14. Taking the origin of co-ordinates at the point corresponding to the geometrical image of

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[1] *Loc. cit.*

one edge of the slit (instead of the center as before), the integral (113) becomes

$$I_{\prime\prime\prime} = A'' \int_0^{\sigma} (A + B\xi) \frac{\sin^2 \frac{\pi}{a_0} \left\{ a - \left(\xi + \frac{\sigma}{2} \right) \right\}}{\left[\frac{\pi}{a_0} \left\{ a - \left(\xi + \frac{\sigma}{2} \right) \right\} \right]^2} d\xi \,. \qquad (115)$$

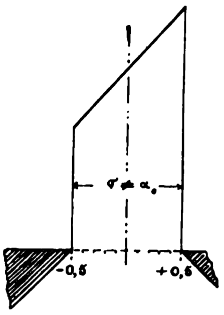

FIG. 14.

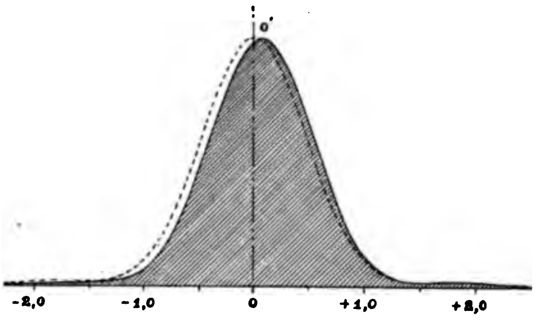

FIG. 15.

I have evaluated this integral by mechanical quadrature for the special case $A = \frac{1}{2}$, $B = \frac{1}{2a_0}$, and $\sigma = a_0$ (*i. e.*, the case in which the angular width of the slit is equal to the resolving power of the view telescope), and the intensity of illumination at one edge, $\xi = 0$, is one-half that at the other, $\xi = a_0 = \sigma$. The results to three places of decimals are tabulated in terms of fractional parts of $\frac{a}{a_0}$ in Table V and plotted in Fig. 15. In both the table and the figure the origin of co-ordinates has been shifted back to the center of the geometrical image.

An examination of these results shows that the position of maximum brightness in the spectral image of the slit is displaced in this case about $0.08\,a_0$ from the center of the geometrical image. This is just a little more than the limiting accuracy ϵ of the instrument, *i. e.*, a uniform variation of 50 per cent. in intensity of illumination from edge to edge of the slit will displace the center of the physical spectral image by an amount somewhat exceeding the limiting accuracy of measurement.

TABLE V.

$\frac{a}{a_0}$	$I_{\dots}=f(\xi)$	$\frac{a}{a_0}$	$I_{\dots}=f(\xi)$	$\frac{a}{a_0}$	$I_{\dots}=f(\xi)$
−2.45	0.011	−0.75	0.235	+0.95	0.148
−2.35	.011	−.65	.317	+1.05	.090
−2.25	.012	−.55	.429	+1.15	.054
−2.15	.014	−.45	.552	+1.25	.036
−2.05	.015	−.35	.672	+1.35	.030
−1.95	.018	−.25	.798	+1.45	.030
−1.85	.020	−.15	.898	+1.55	.032
−1.75	.023	−.05	.968	+1.65	.033
−1.65	.026	+.05	1.000	+1.75	.031
−1.55	.028	+.15	0.987	+1.85	.027
−1.45	.030	+.25	.933	+1.95	.022
−1.35	.032	+.35	.844	+2.05	.017
−1.25	.038	+.45	.727	+2.15	.013
−1.15	.048	+.55	.595	+2.25	.011
−1.05	.068	+.65	.462	+2.35	.010
−0.95	.102	+.75	.337	+2.45	.010
−0.85	.153	+.85	.231	……	….

Second, suppose

$$f(\xi) = C\sqrt{\xi} \; . \qquad (116)$$

This represents a progressively increasing illumination from edge to edge as graphically illustrated in Fig. 16.

With the origin of co-ordinates at one edge of the slit as before, the integral (113) reduces to the form

$$I_{\prime\prime\prime} = A''' \int_0^{\sigma} \sqrt{\xi} \frac{\sin^2 \frac{\pi}{a_0}\left[a - \left(\xi + \frac{\sigma}{2}\right)\right]}{\left[\frac{\pi}{a_0}\left\{a - \left(\xi + \frac{\sigma}{2}\right)\right\}\right]^2} d\xi \; . \qquad (117)$$

This integral has been evaluated for a slit width $\sigma = a_0$ as before for the special case $C = 1$. The results are tabulated and plotted in terms of $\frac{a}{a_0}$ as in the preceding case in Table VI and Fig. 17.

The position of maximum intensity, o′ is, in this case, displaced about $0.13\,a_0$ from the center of the geometrical image, *i. e.*, about twice the limiting error of measurement.

Cases in which the illumination of the slit is of the nature of that just investigated are frequently met with in spectrometric work on the Sun and planets when the image of these bodies is placed eccentrically on the slit or when particular portions of the surface, such as the Sun-spots or solar prominences, are under examination. In the latter case the illumination is likely to be of the nature of that assumed in (114) and (115), and the effect of the variation in intensity of the image on the measured wave-lengths of the spectral lines can be disregarded, as we have seen, only when said variation is less than 50 per cent.

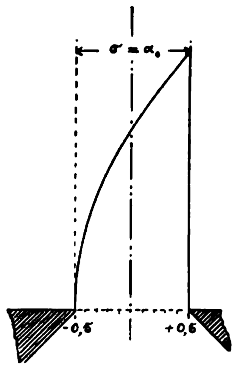

FIG. 16.

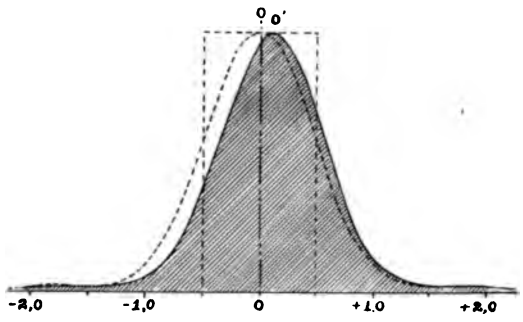

FIG. 17.

In the case of measurements of the velocity of rotation the slit is generally placed tangentially to the limb of the Sun or planet, and the conditions of illumination are then more gener-

TABLE VI.

$\frac{a}{a_0}$	I...	$I'=f(\gamma)$[1]	$\frac{a}{a_0}$	I...	$I'=f(\gamma)$[1]
−1.0	0.062	0.11	+0.00	0.969	1.00
−0.9	.090		+0.1	1.000	
−0.8	.136	0.24	+0.2	0.985	0.92
−0.7	.204		+0.3	.925	
−0.6	.295	0.45	+0.4	.827	0.71
−0.5	.406		+0.5	.702	
−0.4	.533	0.71	+0.6	.564	0.45
−0.3	.665		+0.7	.426	
−0.2	.784	0.92	+0.8	.301	0.24
−0.1	.896		+0.9	.198	
−0.0	.969	1.00	+1.0	.120	0.11

---

[1] For the purpose of comparison the values of I', which expresses the distribution in intensity in the image of a slit of the same width uniformly illuminated, are given in columns 3 and 6. See *Phil. Mag.* 43, 323, Table I; ASTROPHYSICAL JOURNAL, 3, 333 *et seq.* The curve I' $=f(\gamma)$ is plotted in dotted lines in both Fig. 15 and Fig. 17.

ally such as are represented by the distribution assumed in (116) and (117). For in the case of the Sun the variation in the intensity of radiation from the center to the edge is of the nature shown by the curves of Fig. 1 of the preceding paper of this series,[1] and may be represented by the general expression

$$i = \phi\,(\xi^2 + \eta^2)^{\frac{1}{2}}\,. \tag{118}$$

The effective intensity $f(\xi)$ at any point on the axis $\eta = 0$ will be found for this case by integrating the expression

$$f(\xi) = \int_0^{\sqrt{R^2-\xi^2}} \phi\,(\xi^2 + \eta^2)^{\frac{1}{2}} \frac{\sin^2 \frac{\pi}{a_0}(a-\eta)}{\left[\frac{\pi}{a_0}(a-\eta)\right]^2}\,d\eta\,. \tag{119}$$

At the edge of the Sun the value of η increases very rapidly with respect to ξ, and for large values of η the integral

$$\int_0^{\eta} \frac{\sin^2 x}{x^2}\,dx$$

rapidly approaches a constant value. Hence for the purposes of the present general investigation in which we are concerned more with the form of $f(\xi)$ than with its absolute value, we may neglect the second factor of the term under the integral sign of (119) and simply write

$$f(\xi) \cong \int_0^{\sqrt{R^2-\xi^2}} \phi\,(\xi^2 + \eta^2)\,d\eta\,. \tag{120}$$

This integral was evaluated by the writer several years ago (in connection with another research by Professor Michelson), for the particular value of $\phi\,(\xi^2 - \eta^2)$ corresponding to wave-length $\lambda = 5790$ tenth-meters, as given in Vogel's tables. The results were published in the form of a curve (Fig. 5) in Michelson's paper in the *Philosophical Magazine*.[2] An examination of this

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[1] F. W. VERY, "The Absorptive Power of the Solar Atmosphere." *Misc. Sci. Papers*, Allegheny Observatory, No. 9; ASTROPHYSICAL JOURNAL, **16**, 73. See also VOGEL, "Spectralphotometrische Untersuchungen," *Monat. d. K. Akad. d. Wiss.*, Berlin, March 1877; pp. 23, 24, Plate 11.

[2] "Application of Interference Methods to Astronomical Measurements," **30**, 1.

curve will show that for small values of ξ the function $f(\xi)$ can be very closely represented by the parabola

$$f(\xi) = C\sqrt{\xi}$$

which is the form of function used in (116) and (117) already examined.

The effect of this inequality of illumination is, as we have already seen, to displace the spectral image of any line by an amount considerably in excess of the limiting accuracy of measurement. The exact amount of the displacement will depend (*a*) on the width of the slit in comparison with the diameter of the solar image, (*b*) on the position in which the latter is placed with reference to the slit opening. In the case already investigated in (117) we have assumed that the photospheric edge of the solar image is placed tangent to the outer edge of the slit so that when $\xi = o$, $f(\xi)$ is also zero.[1] If the image overlaps the slit, the conditions approximate more nearly those assumed in (114) and (115) and the displacement is less; if the edge of the image is within the slit, the displacement is even greater. Thus when the edge is coincident with the center of the slit, the position in which it is generally placed for velocity of rotation measurements, the displacement of the central point of intensity from the geometrical center will be nearly 0.6 of the half width of the slit, *i. e.*, about 0.3 a, or four times the limiting accuracy ϵ.

The direction of the displacement in the spectrum will depend on the position of the solar image with reference to the direction of deviation of light by the spectroscope train. If the edge of the image is on that side of the slit corresponding to the red end of the spectrum, the displacement will be toward the violet, and the wave-length derived from the measurement will be too small; if turned in the opposite direction the wave-length will be correspondingly too large. The sign of the displacement will, therefore, change not only as we shift the solar image so

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[1] This of course is only an approximation to the actual conditions at the edge of the Sun. There is, however, such a sharp demarcation in intensity of total radiation between the photosphere and the chromosphere and outlying corona that the approximation is in most cases not far from the truth.

that first one edge and then the other falls on the slit; but also as we reverse the direction of deviation of the spectroscope train, "right" or "left," leaving the position of the solar image unchanged. If we therefore attempt to determine the velocity of rotation of a body by the direct measurement of the separation of the spectra from the opposite edges of the slit image, the total error in any one position of the spectroscope will be twice the error of displacement noted above. If we then take a corresponding series of measurements with the direction of dispersion reversed, the errors of displacement will be of the same magnitude as before, but reversed in sign; hence the total difference in measurement will be four times the individual displacement in any one position of image and spectroscope.

Errors of such magnitude as these cannot, of course, be disregarded, even though they may be eliminated by the exact reversal of the relative positions of image and spectroscope. I have, however, failed to find any reference to this particular source of error in the papers of the investigators who have given us our best spectroscopic determinations of velocity of solar rotation. Crew, indeed, in his second investigation[1] notes that the results of his measurements differ with grating "right" and grating "left," but he ascribes this difference to an entirely different cause, *i. e.*, the local heating of the slit jaws. This will undoubtedly produce an effect unless the greater part of the solar image is cut off by a suitable screen interposed in front of the slit, but even when this is not done the total displacement of the slit jaws due to this cause can hardly, in the opinion of the writer, be as great as it is necessary to assume to explain the observed differences of measurement. To do this it is necessary, as Crew has shown, to assume a change of temperature of about 15° C.[2] of each jaw between each measurement, in an interval of only about one minute, and to assume, further, that the expansion due to this change in temperature is all toward the

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[1] "On the Period of Rotation of the Sun," *Am. Jour. Sci.*, **38**, 204.

[2] The assumption of a difference of 10° C., made in Crew's **paper, p. 210,** explains only about two-thirds of the observed **differences of equatorial velocities** with grating "right" and grating "left."

slit opening. Crew observed actual differences of temperature of 10° between two thermometers placed on the two sides, but the change in the slit jaws themselves would be probably much less on account of their own mass and the masses of surrounding and attached metal. Likewise, the jaws when heated, would, if of the usual double-motion construction, expand in both directions. Lastly, if the change of temperature explanation were the correct one, there would be a continual and progressive shift of the spectral image during the entire interval of measurement, and this effect would not have been likely to escape the attention of so careful and accurate an experimentalist as Professor Crew.

On the other hand, if the width of the slit and the setting of the edge of the solar image corresponded to the conditions assumed in the previous integration of (117) the resulting displacement of the spectral images "right" and "left" would *fully* explain and account for the observed differences of measurement. For, as we have shown, the total difference of measurement to be expected is four times the individual displacement of any one image, and this latter is $0.13a_0$ for the conditions assumed. In this instrument the aperture and the focal length of the view telescope are 4 inches and 94 inches respectively. Hence for the D lines the linear value of a_0 is

$$a_0 f = \frac{0.0005896}{94} \times 4 = 0.014 \text{ mm} .$$

Hence the total difference $= 4 \times 0.13a_0 = 0.52a_0$ is in linear measure

$$0.014 \text{ mm} \times 0.52 = 0.0073 \text{ mm} .$$

The total observed difference in measurement amounted to about 0.015 revolutions of the micrometer screw, or, since the latter is of 0.5 mm pitch, to

$$0.0075 \text{ mm} ,$$

or almost exactly the quantity required by theory. When, therefore, the cause of displacement investigated above is taken into account in Crew's measurements, there is no discrepancy remaining to be explained.

The results already obtained indicate the care which it is necessary to take in determining the exact distribution of light in the slit image when the latter is necessarily variable, as in the preceding case. If this cannot be determined, the only way to avoid sensible errors in the wave-length measurements is to secure and maintain an exact centering of the image on the slit, so that the distribution of light over the slit opening is symmetrical about a center line. A case of great importance in this connection is that of determinations of wave-length in stellar spectra for the purpose of measuring motions in the line of sight, etc., with the compound slit spectroscope. The image of the star, as formed on the slit by the main telescope objective, is, if the latter is free from unsymmetrical aberration, a symmetrical diffraction pattern. If the slit is placed in the focal plane of the main objective, the theoretical distribution of light in this image is, for any given wave-length, represented by the usual expression (4), *i. e.*,

$$I_c^2 = A \frac{J_1^2\left(\frac{\pi}{a_0}\xi\right)}{\left(\frac{\pi}{a_0}\xi\right)^2} .$$

In long photographic exposures, the actual effective distribution of light in the slit image is somewhat different from this, owing to atmospheric and instrumental disturbances which broaden the image into what Newall has very aptly termed a "tremor disk." The determination of the exact distribution of light in such a disk is a matter of considerable uncertainty, since the broadening results not only from vibrations of the image, but also from temporary changes of focus and of chromatic dispersion and aberration due to passing air-waves of variable intensity. Under good conditions of "seeing," however, the principal cause of the broadening may be regarded as due to vibrations, and under such conditions we may derive an expression which will represent at least a closely approximate distribution of light in the tremor disk, from the law of probability.

The general expression which represents the probable law of distribution of errors, or, in this case, of displacements from a central position, is

$$y = e^{-h^2\xi^2} \tag{121}$$

and the most probable error (*i. e.*, displacement) is that for which $y = 0.5$ and is given by the relation

$$\xi_0 = P = \frac{0.4769}{h} \tag{122}$$

In the present case it seems a fair assumption to consider that the most probable displacement of the image will be about $\frac{1}{2}\, a_0$, *i. e.*, half the resolving power of the main telescope objective. This assumption gives us for h

$$h = \frac{0.9538}{a_0}\ , \tag{123}$$

which substituted in (121) gives us for y

$$y = e^{-0.9097\frac{\xi^2}{a_0^2}}\ . \tag{124}$$

The resulting distribution in intensity in the tremor disk will then be represented by the integral

$$\int_{-\infty}^{+\infty} e^{-0.9097\frac{\xi^2}{a_0^2}} \frac{J_1\left(\frac{\pi}{a_0}\xi\right)}{\left(\frac{\pi}{a_0}\xi\right)^2} d\xi = f(\xi)\ , \tag{125}$$

or if we assume a rectangular aperture as before, by

$$I_t^2 = \int_{-\infty}^{+\infty} e^{-0.9097\frac{\xi^2}{a_0^2}} \frac{\sin^2\frac{\pi}{a_0}\xi}{\left(\frac{\pi}{a_0}\xi\right)^2}\, d\xi = f(\xi)\ , \tag{126}$$

and the resulting distribution in the spectral image of the slit of width σ_0 will be

$$I_{,,,}^2 = \int_{-(\sigma_2-\sigma_1)}^{+\sigma_1} I_t^2 \frac{\sin^2\frac{\pi}{a_0}(a-\xi)}{\left[\frac{\pi}{a_0}(a-\xi)\right]^2} d\xi\ . \tag{127}$$

In the integration of (126) and (127) it is convenient to express a_0 in terms of σ_0, the width of the spectroscope slit.

The usual practice is to make this width equal to $2\,a_0$[1] so as to just include the central diffraction disk of the undisturbed star image. Substituting this value of σ_0 in the above equations we obtain

$$I_t^2 = \int_{+\infty}^{-\infty} e^{-3.64\frac{\xi^2}{\sigma_0^2}} \frac{\sin^2 \frac{2\pi}{\sigma}\xi}{\left(\frac{2\pi}{\sigma}\xi\right)^2} d\xi \;. \tag{128}$$

This has been integrated by mechanical quadrature as before. The results are tabulated in Table VIII and plotted in Fig. 18.

TABLE VIII.

$\frac{a}{\sigma}$	I_t^2	$e^{-A'\xi^2}$	$I_t^2 - e^{-A'\xi^2}$
±0.00	1.000	1.000	0.000
±0.10	0.972	0.973	−.001
±0.20	.888	.892	−.004
±0.30	.771	.773	−.002
±0.40	.632	.633	−.001
±0.50	.490	.490	±.000
±0.60	.361	.358	+.003
±0.70	.254	.247	+.007
±0.80	.171	.161	+.010
±0.90	.111	.099	+.012
±1.00	.069	.057	+.012

The full curve, I_t, closely resembles the exponential curve $e^{-A'\xi^2}$. We have therefore substituted for (128) a second empirical curve of this form having such a value of A' that the two curves coincide at the point $x = a_0 = \frac{1}{2}\sigma_0$. This gives us for A'

$$A' = 2.854 \;,$$

and for $f'(\xi)$

$$e^{-2.854\frac{\xi^2}{\sigma_0^2}} \cong I_t^2 \;. \tag{129}$$

The values of $f'(\xi)$ from (129) are tabulated in the third column of Table VIII and plotted as the dotted curve in Fig. 18. Over all that part of the tremor disk which is likely to fall within the slit opening, *i. e.*, from $\xi = 0$ to $\xi = \pm 2\,a_0$, the coin-

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[1] This is twice as large as the value of σ assumed in the previous cases. Compare Figs. 14, 16, and 18.

cidence between the two curves, I_t^2 and $f'(\xi)$, as given by (129), is closer than the uncertainty as to the exact form of I_t^2 itself.

Assuming that the effective size of the tremor disk is defined by the limits $m\,m$ such that $I_m^2 = 0.04 I_0^2$, we have under the conditions assumed above

$$m\,m = W \cong 4.5\alpha_0 = 2.25 m_0\,m_0 \;; \tag{130}$$

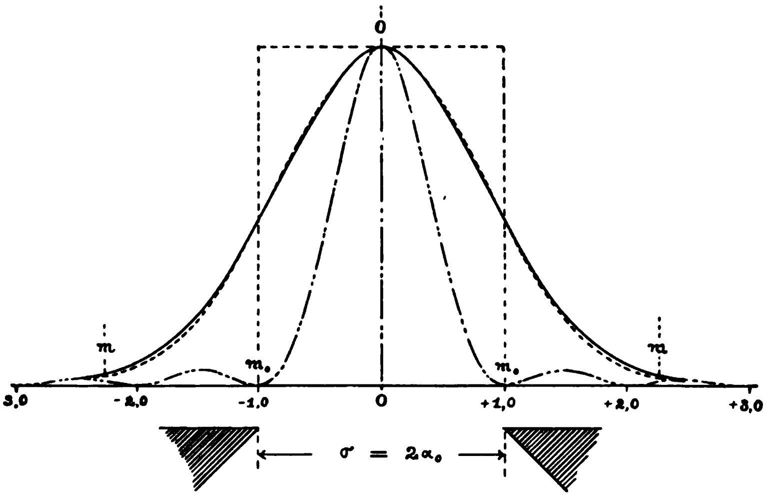

FIG. 18.

i. e., the tremor disk is about two and one-quarter times the size of the true central diffraction disk of the star. When the tremor disk is centered on the slit opening, the percentage of the total quantity of light in the image which enters the slit is of course given by the expression

$$\frac{2}{\sqrt{\pi}}\int_{-\frac{1}{2}\sigma}^{+\frac{1}{2}\sigma} e^{-2.854\frac{\xi^2}{\sigma_0^2}}\,d\xi \cong 0.76 \;; \tag{131}$$

i. e., the time of exposure is increased about one-third by the effect of atmospheric and instrumental vibrations of the previously assumed probable magnitude of $\frac{1}{2}\alpha_0$.

This result agrees fairly well with the actual exposure times which Campbell finds necessary in obtaining well defined spectra with the Mills slit spectroscope as compared with those required on the same stars with the Harvard objective prism spectrograph, when we allow for the difference in the resolving power and light efficiency of the two instruments. It is lower than the estimate given by Frost in his description of the Bruce spectrograph, but for some reason the latter is somewhat less efficient in regard to exposure times than the Mills instrument.[1]

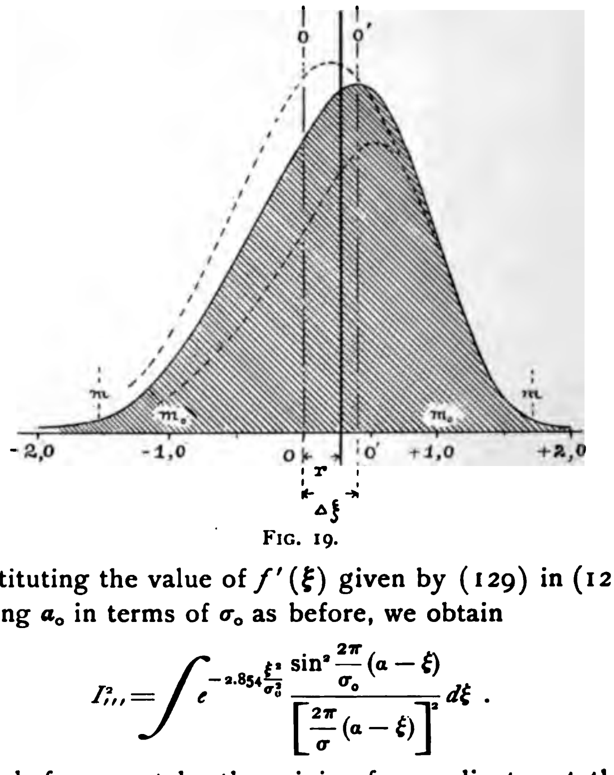

FIG. 19.

Substituting the value of $f'(\xi)$ given by (129) in (127), and expressing a_0 in terms of σ_0 as before, we obtain

$$I^2_{,,,}=\int e^{-2.854\frac{\xi^2}{\sigma_0^2}}\frac{\sin^2\frac{2\pi}{\sigma_0}(a-\xi)}{\left[\frac{2\pi}{\sigma}(a-\xi)\right]^2}d\xi\ . \qquad (132)$$

If, as before, we take the origin of co-ordinates at the point corresponding to the geometrical image of one edge of the slit and consider the most general case in which the center of the tremor disk may be located anywhere within the slit opening, we have as before for ξ

$$\xi=\xi'+\frac{\sigma}{2}+\Delta\sigma\ ,$$

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[1] Compare result on p. 20 of Frost's paper, ASTROPHYSICAL JOURNAL, 15, with those given by Campbell, ASTROPHYSICAL JOURNAL, 8, 141.

where $\Delta\sigma$ is the amount by which the center of the tremor disk is displaced from the center of the slit. Substituting, this gives

$$I^2_{,,,}=\int_0^{\sigma_0} e^{-2.854\frac{(\xi+\frac{\sigma}{2}+\Delta\sigma)^2}{\sigma_0^2}} \frac{\sin^2\frac{2\pi}{a_0}\left[a-\left(\xi+\frac{\sigma}{2}+\Delta\sigma\right)\right]}{\left[\frac{2\pi}{a_0}\left\{a-\left(\xi+\frac{\sigma}{2}+\Delta\sigma\right)\right\}\right]^2} d\xi \,. \qquad (133)$$

The only case for which $I^2_{,,,}$, (133), is symmetrical is that for which $\Delta\sigma = 0$. The center of intensity is then at the point $\xi = \frac{1}{2}\sigma_0$, and there is no error of displacement.

In order to find the relation between the error of centering, $\Delta\sigma$, and the resulting displacement $\Delta\xi$ of the spectral image, I have integrated (133) for different values of $\Delta\sigma$ from $\Delta\sigma = 0.1\sigma_0$ to $\Delta\sigma = 0.5\sigma_0$. The resulting values for $I^2_{,,}$ are given in Table IX and the curves for $\Delta\sigma = 0.3\,\sigma_0$ (full) and $\Delta\sigma = 0.1\,\sigma_0$ and $0.5\,\sigma_0$ (dotted) are plotted in Fig. 19.

TABLE IX.

$\frac{a}{\sigma}$	$I_{,,,}$ for Different Values of $\frac{\Delta\sigma}{\sigma}$				
	$\Delta\sigma = 0.1\sigma$	$\Delta\sigma = 0.2\sigma$	$\Delta\sigma = 0.3\sigma$	$\Delta\sigma = 0.4\sigma$	$\Delta\sigma = 0.5\sigma$
−1.00			0.018		
−0.90			.021		
− .80			.034		
− .70			.058		
− .60			.107		
− .50			.191		
− .40			.296		
− .30			.422		
− .20			.550		
− .10			.678		
− .05	0.948		.742		
± .00	.977	0.909	.803	0.677	0.545
+ .05	.995	.948	.858	.741	.611
+ .10	1.000	.975	.903	.799	.672
+ .15	0.988	.986	.935	.844	.727
+ .20	.959	.978	[.946]	.872	.765
+ .25	.912	.948	.934	.877	.783
+ .30		.893	.896	.855	.776
+ .35		.817	.832	.807	.742
+ .40		.724	.746	.732	.682
+ .50			.532	.534	.519
+ .60			.315		
+ .70			.150		
+ .80			.061		
+ .90			.024		
+1.00			.016		

The positions ξ_0 of the points of maximum intensity in the curves $I^2_{\prime\prime\prime}$ are found to be as follows:[1]

$$\begin{array}{llll}
\text{For } \Delta\sigma = 0.1\sigma_0, & \xi_0 \cong 0.595\sigma_0 & \Delta\xi \cong 0.095\sigma_0 = 0.19\alpha_0 \\
\Delta\sigma = 0.2\sigma_0, & \xi_0 \cong 0.655\sigma_0 & \Delta\xi \cong 0.155\sigma_0 = 0.31\alpha_0 \\
\Delta\sigma = 0.3\sigma_0, & \xi_0 \cong 0.700\sigma_0 & \Delta\xi \cong 0.200\sigma_0 = 0.40\alpha_0 \\
\Delta\sigma = 0.4\sigma_0, & \xi_0 \cong 0.735\sigma_0 & \Delta\xi \cong 0.235\sigma_0 = 0.47\alpha_0 \\
\Delta\sigma = 0.5\sigma_0, & \xi_0 \cong 0.765\sigma_0 & \Delta\xi \cong 0.265\sigma_0 = 0.53\alpha_0 \,.
\end{array}$$

The relation between $\Delta\sigma$ and $\Delta\xi$ is plotted in Fig. 20 (full curve). As will be seen by the dotted curve it can be represented very closely by the empirical equation

$$\Delta\xi = \frac{7}{8}\alpha_0 \sqrt[3]{\left(\frac{\Delta\sigma}{\sigma}\right)^2}\,. \tag{134}$$

In measuring the apparent position of the displaced diffraction image the tendency will be, as before, to compromise between the point of maximum intensity, o', and the point midway between the apparent edges, $m\ m$, (defined as before), of the line. The resultant setting, r, for the cross-wire will be at a point not far from $\frac{2}{3}\Delta\xi$. We may therefore write

$$\left.\begin{array}{l}
\Delta_m\xi = \text{measured displacement} \cong \dfrac{2}{3}\Delta\xi \\
\cong 0.58\alpha_0 \sqrt[3]{\left(\dfrac{\Delta\sigma}{\sigma}\right)^2}
\end{array}\right\}. \tag{135}$$

In order that the displacement shall not be great enough to affect the accuracy of measurement we must have as before

$$\Delta_m\xi \leqq \epsilon\,,$$

or in this case from (14) and (135)

$$0.07 \geqq 0.58 \sqrt[3]{\left(\frac{\Delta\sigma}{\sigma}\right)^2}\,, \tag{136}$$

or

$$\frac{\Delta\sigma}{\sigma_0} \leqq .04\,.$$

i. e., the star image must be centered on the slit with an error not exceeding 4 per cent. of the slit width.

This is a condition which has apparently never before been

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[1] The points of maximum lie between the numbers in heavy type in the table.

recognized as necessary to accuracy in the use of the slit spectroscope. Care has of course always been taken to keep the star image as nearly central as possible in the slit opening, but the object aimed at has been simply to utilize the greatest amount of light and shorten the time of exposure as much as possible. But the above investigation shows that the requirements of accuracy and the avoidance of constant errors require a far greater degree of care in centering and following than is usually deemed necessary, greater in fact than many of the devices now used for following make possible.

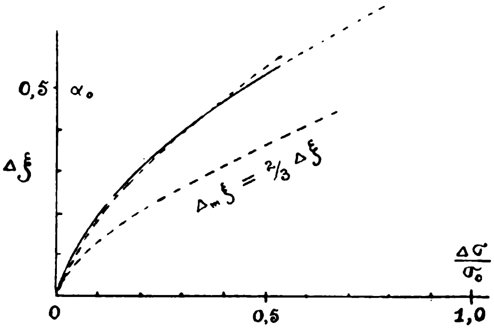

FIG. 20.

This question is one of such great importance in view of the minuteness of the displacements upon which determinations of motions in the line of sight depend, that it may be interesting to calculate the error in kilometers per second produced by an error of say 10 per cent. in the centering of the star image on the slit. From the previous results we find, for $\frac{\Delta\sigma}{\sigma_0}=0.10$,

$$\Delta_m\xi = 0.13\alpha_0 \ . \qquad (137)$$

Since the angular resolving power α_0 is the same for both collimator and view telescope, we can readily establish a relation between α_0, $\frac{d\theta}{d\lambda}=$ the dispersion of the spectroscope train, and v_s the motion in the line of sight of the body under examination. From the well-known relations

$$v_s=\frac{\Delta\lambda}{\lambda}V$$

$$f\alpha_0=\frac{\lambda}{b}f=\frac{\lambda}{\beta}$$

and

$$\Delta\lambda=\frac{\Delta\xi}{\frac{d\theta}{d\lambda}} ,$$

we get at once

$$v_s = \frac{\Delta\xi}{\frac{d\theta}{d\lambda}} \cdot \frac{V}{\lambda} \,,$$

and for the value of $\Delta_m\xi$ assumed in (137)

$$\delta v_s = \frac{0.13\,V}{b\frac{d\theta}{d\lambda}} = \frac{0.13\,V}{R} \qquad (138)$$

$$= \frac{38000}{r} \text{ km per sec. ,}$$

where r is the spectroscopic resolving power of the prism train.

The following table contains the approximate resolving powers of the more important instruments that have been used in line of sight work and the corresponding error δv_s produced by a 10 per cent. error of centering of the star disk from (138):

TABLE X.

Name of Instrument	Spectroscope Train	Approximate r for $H\gamma$	δv_s Kilometers per Second
Potsdam II (Vogel)	2 Compound Prisms	about 40,000	about 0.9
Pulkowa (Bélopolsky)............			
Bruce I (Newall)[1]................	1 Simple Prism	22,000	1.7
Mills (Campbell)[2]................	3 " Prisms	74,000	0.5
McMillin (Lord)[3].................	2 " "	42,000	0.9
Potsdam III (Vogel)[4].............	3 " "	63,000	0.6
Bruce II (Frost)[5]................	3 " "	110,000	0.2

An examination of this table shows that even for this small error in centering the errors in the resulting determinations of v_s are sufficiently large to account for a large part of the differences of measured velocities between some of the different observers. When we remember the difficulty of keeping a faint star *accurately* centered on the slit, and remember, also, that any constant asymmetry of the tremor disk itself due to peculiar instrumental conditions will notably increase the effect of a given displacement from the center, we can readily see that we have here what may be a constant source of error of the most serious kind, and in some cases of even greater magnitude than indicated in the above table. If, for example, the error of centering were

[1] ASTROPHYSICAL JOURNAL, 3, 266.

[2] *Ibid.*, 8, 123.

[3] *Ibid.*, 4, 50.

[4] *Ibid.*, 11, 393.

[5] *Ibid.*, 15, 1.

for any reason constant in direction with reference to the large telescope, any reversal of the spectroscope with reference to the latter would introduce differences in observed positions of the lines, and hence of v_s of twice the amount indicated in Table X.

As this error is purely one of manipulation, we cannot in general make any correction or allowance for it *after* the photographic record has been taken. The utmost care, therefore, must be exercised in order to attain the accuracy of centering and following requisite to eliminate it completely, as indicated in (136). To do this we should, as far as possible, fulfill the following general conditions:

1. Have a sharp, well-defined, and symmetrical image of the star formed on the slit of the spectrograph. If the main image-forming objective is a visual refractor, this will necessitate in general the use of a correcting lens, and this should be so designed as to be free from spherical and chromatic aberration for the region of the spectrum under examination, and so mounted that its principal optical axis *coincides* with that of the main objective and the axis of collimation of the spectroscope itself. The light from the other portions of the spectrum should be cut out from the following eyepiece by use of suitable screens or screening devices[1] placed between the slit and eyepiece. On account of the perfect achromatism of the reflecting telescope this form of objective has great advantages over the refractor in this connection; another reason why such instruments should be given the preference for spectroscopic work.[2]

2. The guiding device should use as a reference mark for centering the star image, some point on the slit itself, in order

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[1] Such, for example, as the optical color screen described by the writer in this JOURNAL, 3, 169.

[2] The importance and value of the reflecting mirror as compared with the refractor in spectroscopic work have been urged upon the attention of astrophysicists by the writer for many years. See *Phil. Mag.*, July and October, 1894; *A. and A.*, December, 1894; ASTROPHYSICAL JOURNAL, January, 1895; *ibid.*, March, 1895; *ibid.*, March, 1896; *ibid.*, May, 1896; *ibid.*, October, 1896; *ibid.*, February, 1897; *ibid.*, February, 1898; *Pop. Astron.*, February, 1898, etc. The advantages of the reflector in this line of work are now being more generally recognized, and a number of large instruments of this type are planned or in actual course of construction by our large astrophysical observatories.

to avoid any errors of parallax or relative displacement of the slit and guiding cross-wires. For this reason I believe a modification of the Huggins reflecting slit and following device is better adapted to this purpose than any other form yet invented. The use of an auxiliary independent guiding telescope such as is proposed with the new Potsdam instrument would seem to be especially dangerous.

3. If the required accuracy of following cannot be attained with the usual slit width $\sigma_0 = 2\,a_0$, then the width should be reduced and the time of exposure correspondingly increased, or else greater spectroscopic resolving power should be used. The effect of decreased slit width will be to reduce the limits of integration in (127) and (133), and correspondingly reduce the resultant asymmetry and displacement of the center of intensity of the spectral image. The result of increasing R will be to decrease the value of δv_s in (138) for a given value of $\Delta\sigma$.

In this connection it may also be noted that "bad seeing," which results in an increase in size of the tremor disk, will reduce the effect of a given percentage error of centering $\frac{\Delta\sigma}{\sigma_0}$ by flattening the curve I_t^2 of Fig. 18, and thus reducing the difference between the intensity of illumination at different parts of the slit image. When the "seeing" is "bad," therefore, the slit may be opened wider without increasing the effect of errors of following.

B (4). It was the intention of the writer to take up also, in connection with the present paper, the discussion of effects of errors of mechanical design and construction, with reference particularly to the avoidance of flexure and strain resulting from changes in position or changes of temperature of the instrument during use. The present discussion has, however, so far exceeded the limits originally set that it seems better to reserve this part of the subject for a future paper in which the description of the spectrographs and some other astrophysical instruments of the new Allegheny Observatory will also be taken up.

ALLEGHENY OBSERVATORY, 1901–1902.

ON SCREENS TRANSPARENT ONLY TO ULTRA-VIOLET LIGHT AND THEIR USE IN SPECTRUM PHOTOGRAPHY.

By R. W. WOOD.

ANYONE who has repeated Tyndall's beautiful lecture experiment of kindling a pine stick in the dark heat focus of a burning-glass, concentrating light from which the visible radiations have been removed by means of a solution of iodine in bisulphide of carbon, must have wished that we possessed a screen opaque to visible light and transparent to the ultra-violet.

I have recently succeeded in making a screen quite transparent to these radiations, though a gas flame cannot be seen through it. By combining it with a large condensing lens and an arc-lamp, it is possible to form a dark focus of ultra-violet light in which a lump of uranium nitrate glows with a vivid green phosphorescence like a great emerald.

Aside from giving us the means of performing a most beautiful lecture experiment, these screens make it possible to photograph the ultra-violet lines in grating spectra of higher orders than the first, entirely uncontaminated by the visible radiations which overlie them. Other applications at once suggest themselves, such as the complete removal of the highly actinic blue and violet rays, in certain investigations of the ultra-violet region where the long exposures necessary are apt to produce fogging of the plates. It seems quite possible, too, that photographs of the Moon, planets, and nebulæ, taken by means of ultra-violet light, may furnish valuable data, as I shall attempt to show at the end of this paper.

The substance which has made possible the production of such a screen is nitroso-dimethyl-aniline, the remarkable optical properties of which I have already alluded to in a previous paper. As I have already said, a prism formed of this substance yields a spectrum about thirty times as long as a quartz prism of the same angle, the dispersion somewhat resembling that of selenium. I was of the opinion that the absorption, which commences at about wave-length 0.0005 mm, would increase continuously from this point down to the end of the spectrum, as was found to be the case with selenium. On commencing a study of the absorption, however, I was astonished to find that it ended abruptly a little beyond the H and K lines, and that from this point on the substance was transparent even down to the last cadmium line, of wave-length 0.0002 mm. It at once occurred to me that, if some substance or substances could be found, absorbing the red, yellow, and green, and transparent to the ultra-violet, we could, by combining them with the nitroso compound, produce the long-sought screen.

Very dense cobalt glass, coated with a thin film of gelatine lightly stained with the nitroso, was found to be transparent only to the extreme red and the ultra-violet, and the red was eventually removed by means of a thin sheet of Chance's "signal-green" glass, such as is used for one of the reflectors in the Ives Kromskop. This combination is wholly opaque to visible light, while freely transmitting everything between wave-lengths 34 and 38. Of course, the employment of glass screens limits the ultra-violet transmission, and a screen of this description is useful chiefly for lecture demonstrations. Considerable care must be used in the adjustment of the strength of the solution of the nitroso in gelatine, otherwise the intensity of the ultra-violet light is considerably weakened. The best strength is such as will be just sufficient to remove the blue and violet light transmitted by dense cobalt glass. Quite a number of trials will be found necessary in adjusting the densities of the three components of the screen to secure the maximum effect, but when the balance is just right, it is possible to form a focus in which a piece of paper is quite invisible, while a mass of crystals of the nitrate of uranium (which I have found superior to anything else) glows with sufficient intensity to be seen from the back of the largest lecture-room. It is best to exclude carefully all light which does not pass through the screen.

With the assistance of one of our students, I am at the present time investigating the absorption of a large number of substances which, so far as I know, have not been previously studied, and I hope in time to dispense with glass entirely, and produce an opaque screen which transmits ultra-violet light down to the end of the spectrum. A tube filled with iodine vapor and furnished with quartz ends, on one of which is a thin film stained with nitroso, transmits all the ultra-violet, and only the extreme red, but it is very inconvenient to work with. For use as a screen in spectrum photography there is no especial object in removing the red, yellow, and green, the nitroso alone blocking out completely the actinic portions of the visible spectrum, which overlie the ultra-violet in the second, and third-order spectra, and I shall next consider solutions of the substance in various fluids in connection with spectrum photography.

I have found that the best method of quickly securing a record of the absorption of a solution is to bring a prismatic layer of the liquid, contained in a quartz cell, before the slit of a quartz spectrograph, and photograph the spectrum of the cadmium spark. We secure in this way a record of the absorption of the liquid in various thicknesses, in the form of a curve, quite similar to the curves laboriously constructed from the readings obtained with the spectro-photometer.[1]

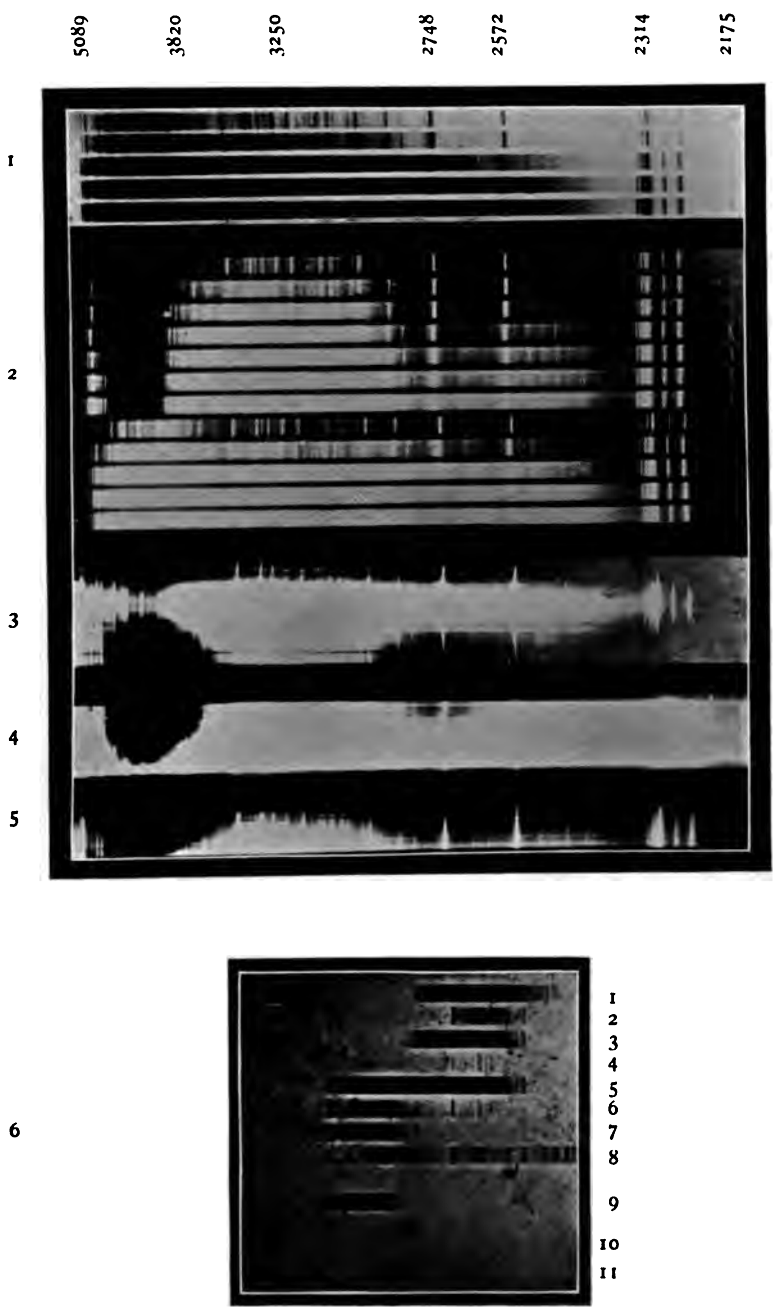
The curve obtained with a solution of the nitroso in glycerine is shown in Plate XII, Figs. 4 and 5. It will be noticed that after a certain thickness has been passed we begin to get a noticeable absorption in the ultra-violet, the form of the curve in this region being well shown in Figs. 3 and 4. The band in the blue and violet is, however, so much heavier that, by employing a film of suitable thickness, we can get complete opacity in this region, combined with almost perfect transparency in the ultra-violet.

[1] It is my intention to prepare a monograph on the absorption of a large number of the aniline dies, and other organic compounds such as the nitroso-dimethyl-aniline' which have not been previously investigated. The spectra will be approximately normal, all on the same scale, and will extend from the C line down to the end of the spectrum. They will be photographed in the manner which I have described, and will, I hope, make it possible for the spectroscopist or physicist to pick out at once the combination necessary to produce any desired result. Preliminary experiments are now in progress to determine the best form to give the apparatus, and the most suitable source of light, and I shall be very glad of any suggestions pertaining either to the apparatus or to particular substances worthy of investigation.

The nitroso is soluble in water, glycerine, ether, alcohol, bisulphide of carbon, and many other fluids, and the region of heaviest absorption varies somewhat with the nature of the solvent, the shift of the band not, however, following Kundt's rule in every case. A stained gelatine film on a quartz plate forms a fairly suitable screen, if we do not wish to photograph below the group of cadmium lines at wave-length 2314. It is opaque, however, to waves much shorter than this. The glycerine solution transmits down to the last cadmium line, $\lambda = 2147$, and some other solvents appear to work equally well.

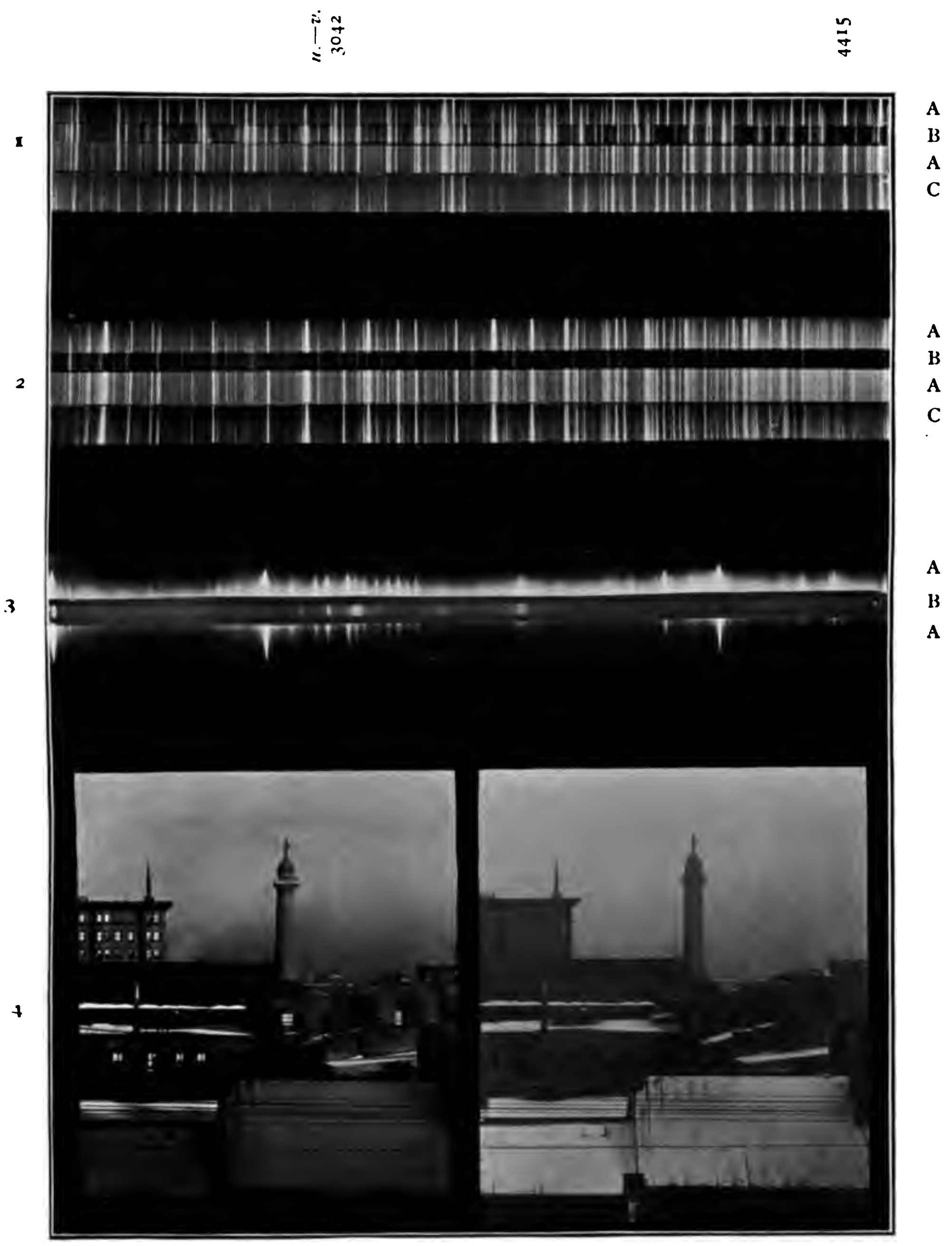
In photographing the spectrum of the cadmium spark in the ultra-violet of the third order, with the fourteen-foot concave grating, I found that the prolonged exposure of the solution in glycerine to the light of the spark resulted in its decomposition. Gas bubbles formed in the thin quartz cell, and, by bridging across the space between the two plates, allowed the passage of blue and violet light. The same thing occurred with pure glycerine under a quartz plate, while glycerine under glass was unaffected, showing that the decomposition was caused by the extreme ultra-violet. In addition to the formation of bubbles a gradual bleaching of the solution occurred. To obviate this difficulty I constructed a small cell of quartz, by cementing two plates together, with a space of about 0.5 mm between them, the cell thus formed being cemented to the bottom of a small thistle tube with a very small bore. By filling the thistle tube with the glycerine solution, a flow took place through the cell at the rate of about a drop every two minutes. This device worked admirably and gave no trouble at all, the cell being placed close to the slit of the grating camera in the path of the convergent beam from the quartz lenz. Another very satisfactory screen can be made by dissolving celluloid (previously boiled for some time in water) in amyl acetate, adding a little nitroso, and flowing the solution on a quartz plate. It is, however, opaque to the last two cadmium lines. The use of the screen necessitates considerable increase in the time of the exposure, the amount varying from two to ten, or even twenty, times, according to the density of the screen. The strength of the glycerine solution must be

PLATE XII.



EFFECTS OF ABSORBING SCREENS.

PLATE XIII.



A B

Effect of Screens Transparent only to Ultra-Violet Light.

PLATE XIII.

B

LTRA-VIOLET LIGHT.

adjusted according to the work required of it; a strong solution gives a wider band in the blue and violet, but diminishes the intensity of the ultra-violet as well. In general, the best results are obtained when the blue line of wave-length 4799 in the spark spectrum of cadmium can be just barely discerned.

In Plate XII, Fig. 1, the wave-lengths of the principal lines in the spark spectrum of cadmium are given for reference. The action of the nitroso screen is well shown in Fig. 2, the spectra being photographed with a small quartz spectrograph made by Fuess. The first seven spectra were taken through the glycerine nitroso cell which I have just described, with the following times of exposure: 5, 10, 15, 20, 30, 45, and 60 seconds. The cell was then removed and the following six spectra taken with exposures 2.5, 5, 10, 15, 20, and 30 seconds. A study of these spectra enables us to calculate just what can be done with this screen, and the necessary increase in the time of exposure resulting from its use.

In Fig. 6, which is a negative, we have the absorption spectra of the various components of the screen which I mentioned in the first part of this paper, taken with exposures of 20 seconds each. The spectra were taken through screens as follows:

1. Nitroso in gelatine on glass (thin film).
2. Nitroso in gelatine on glass (thick film).
3. Nitroso in gelatine on cobalt glass (thin film).
4. Nitroso in gelatine on cobalt glass (thick film), strong ultra-violet absorption.
5. Dense cobalt glass.
6. Turnbull's blue in gelatine.
7. Chance's "signal green" glass (two thicknesses).
8. No screen, 3 seconds' exposure.
9. Cyanine in Canada balsam.
11. Aurantia in collodion.

These photographs were taken on an orthochromatic plate, the yellow and yellow-green being compressed into the small strip which appears alone in No. 11.

The utility of the nitroso screen in photography with the concave grating is very clearly brought out in the photographs of the iron spectrum shown in Plate XIII. These were made with a fourteen-foot grating, with a glycerine nitroso cell before the slit during one of the exposures. Figs. 1 and 2 are from the same plate. Strip B in each was made through the screen, and shows the ultra-violet of the third order, uncontaminated by the blue of the second. In strips A, which were made without the screen, the two orders are mixed. Strips C were made through a glass screen, which cut off the third order ultra-violet, leaving the blue of the second. I have marked a few of the wave-lengths to aid in the identification of the lines. The times of exposure were for strips A and C 10 minutes, for B 50 minutes.

The group of cadmium lines in the neighborhood of wave-length 2314 is, in the second-order spectrum, mixed up with a lot of blue air lines of the first-order spectrum. The separation of the two by the nitroso screen is well shown in Fig. 3, in which the two orders are shown superposed in strips A, and the ultra-violet of the second order in strip B. The exposures in this case were 15 minutes and 2 hours respectively.

Another screen which I believe may prove useful in astrophysical work is made by combining nitroso-dimethyl-aniline with a small amount of the dye uranine, the latter removing the bluish-green portion of the spectrum which affects the photographic plate. By a proper adjustment of the two in gelatine on glass, a screen can be formed which, when used with an ordinary (*i. e.*, not orthochromatic) plate, gives us a photograph made exclusively by ultra-violet light, comprised between wave-length 345 and 365—a rather narrow range. I have made a few photographs with a screen of this description which have brought out some interesting points. In a photograph of the full Moon, taken by ultra-violet light, the contrast between the bright and dark areas is very strongly accentuated, while in photographs of landscapes made in the same way there is almost no contrast at all, except between white objects and objects not white. I have also photographed a collection of rocks and minerals with ultra-violet light and with yellow light. In the negative taken by yellow light there is a great deal of contrast and detail, especially in the marbles and conglomerates, while in the negative taken by ultra-violet light all this is absent, the white specimens coming out very black, with everything else of a thin and almost uniform gray. I hope in the near future to have an opportunity of making some lunar photographs on a large scale, the only instrument at my disposal at the present time being the nine-inch equatorial of the University. Photographing by ultra-violet light appears to diminish the contrast between all objects not white, and to increase the contrast between white objects and those not white. I do not wish to be hasty in drawing conclusions, but it appears to me to be probable that the more luminous portions of the lunar surface, if not as white as plaster of Paris, must at least be much whiter than gray sandstone.

In Plate XIII, Fig. 4, are reproduced two photographs of the same landscape, taken at the same time and under similar conditions of illumination, the one (A) taken on an orthochromatic plate by yellow light through a screen of dense aurantia, the other (B) taken on an ordinary plate by ultra-violet light. The absence of contrast between the chimneys and walls in B is especially noticeable in the right-hand part of the picture. I tried various times of exposure, and the picture reproduced is the best of the lot. Another curious effect is the almost complete absence of shadows in the ultra-violet picture (it was taken in full sunlight like the other), showing that most of the ultra-violet light comes from the sky, which is what we should expect, though we should hardly anticipate that the effect would be so pronounced. This is best seen on the monument and on the snow in the middle distance. The increase of "atmosphere" in the ultra-violet picture is very marked. It is so strong that under-exposed plates fog in the shadows of objects not over one hundred yards from the camera, a circumstance which shows the great scattering power of the air for these short waves. The two pictures are also interesting as showing that our eyes have developed a maximum sensibility for that region of the spectrum which shows terrestrial objects in strongest contrast. Nitroso-dimethyl-aniline is the only substance, other than the ordinary aniline dyes, that I have examined thus far, and I feel very hopeful of finding among the large number of allied substances, absorbing media even more transparent to the ultraviolet radiations than the one which I have described in this paper.

Physical Laboratory,
Johns Hopkins University,
Baltimore, January 1903.

SYSTEMATIC ERRORS IN THE WAVE-LENGTHS OF THE LINES OF ROWLAND'S SOLAR SPECTRUM.

By G. EBERHARD.

IN their investigations with their interference apparatus Messrs. Fabry and Perot[1] have measured the wave-lengths of 33 lines of the solar spectrum, and have compared their values with those given by Rowland in his preliminary table of solar spectrum wave-lengths. In this way they have shown that Rowland's system contains systematic errors of considerable amount in comparison to the accuracy of the relative measurements for small regions of spectrum. They give for a number of lines the ratio $\frac{\lambda\text{ (Rowland)}}{\lambda\text{ (Fabry and Perot)}}$, which in the absence of systematic errors should be constant, and for the sake of the subsequent comparison I have also plotted the numbers of their table on a curve given below.

Although any doubt as to the reality of these systematic errors in Rowland's table is wholly dispelled by the great accuracy attained by Messrs. Fabry and Perot in their investigations, it nevertheless seemed to me to be of interest to examine another independent series of observations—the wave-lengths of 300 solar lines measured by Müller and Kempf—and see whether a comparison of their values with Rowland's would exhibit the same thing. In a similar comparison Müller had already found that "in the central portions of the spectrum between wave-lengths about 550 and 610, negative signs prevail, which leads to the inference of systematic inequalities in one of the two series of measures," etc.[2] I had to take into account the fact that, in consequence of the nature of the grating then employed, which was decidedly inferior in quality to modern gratings, accidental errors of measurement would occur of much larger amount than in the case of Rowland, and that these could only be in

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[1] ASTROPHYSICAL JOURNAL, 15, 270–273, 1902.

[2] *Publicationen des Astrophysikalischen Observatoriums zu Potsdam*, 8, 51.

some measure compensated for by taking the means from a large number of lines.[1] But, on the other hand, Müller and Kempf proceeded with the greatest possible care in building up their system, so that the occurrence of systematic errors, which were dependent upon the wave-length, did not seem to me probable, aside from those errors which might arise from the determination of the constant of the grating.

On carrying out the computations, my suspicions were fully confirmed, as I found that the quotient $\frac{\lambda\ \text{(Rowland)}}{\lambda\ \text{(Müller and Kempf)}}$ exhibited very nearly the same course as the similar quotient between Rowland and Fabry and Perot; but the values of the first quotient disclose very much greater differences for neighboring lines than in the case of Fabry and Perot.

λ (Rowland)	$\frac{\lambda\ \text{(Rowland)}}{\lambda\text{(M. and K.)}}$	λ (Rowland)	$\frac{\lambda\ \text{(Rowland)}}{\lambda\text{(M. and K.)}}$	λ (Rowland)	$\frac{\lambda\ \text{(Rowland)}}{\lambda\text{(M. and K.)}}$	λ (Rowland)	$\frac{\lambda\ \text{(Rowland)}}{\lambda\text{(M. and K.)}}$
4494.738	1.000001	5281.971	0.999967	5775.304	0.999990	6246.535	0.999970
4501.448	0.999986	5283.802	0.999976	5806.950	0.999983	6252.773	0.999964
4508.455	1.000000	5288.705	0.999973	5816.601	0.999988	6256.572	0.999986
4563.939	0.999971	5307.541	0.999978	5831.821	0.999976	6265.348	0.999979
4572.156	0.999984	5324.373	0.999980	5862.582	0.999987	6318.239	0.999971
4703.177	0.999993	5353.571	0.999974	5896.155	0.999984	6322.907	0.999976
4754.225	0.999963	5367.669	0.999977	5934.881	0.999982	6335.554	0.999974
4861.527	0.999977	5383.578	0.999981	5948.765	0.999972	6344.371	0.999980
4890.948	0.999969	5389.683	0.999973	5977.007	0.999983	6355.246	0.999966
4903.502	0.999974	5393.375	0.999964	5987.290	0.999982	6358.898	0.999986
4920.685	0.999979	5405.989	0.999987	6003.239	0.999985	6380.958	0.999973
4924.107	0.999971	5415.416	0.999981	6013.715	0.999981	6393.820	0.999984
4973.281	0.999976	5434.740	0.999987	6024.281	0.999983	6408.233	0.999982
4980.352	0.999966	5487.959	0.999980	6042.315	0.999976	6411.865	0.999982
4999.689	0.999978	5497.735	0.999983	6056.227	0.999977	6421.570	0.999977
5050.008	0.999992	5501.683	0.999975	6065.709	0.999983	6431.066	0.999992
5090.954	0.999968	5528.641	0.999993	6078.710	0.999980	6439.293	0.999987
5133.870	0.999975	5543.414	0.999995	6102.937	0.999980	6450.033	0.999977
5159.231	0.999967	5555.122	0.999991	6122.434	0.999994	6534.172	0.999980
5162.449	0.999971	5624.769	1.000001	6141.938	0.999983	6546.479	0.999972
5172.856	1.000001	5634.171	0.999995	6162.390	0.999977	6563.045	0.999986
5183.791	0.999973	5675.647	0.999980	6180.420	0.999977	6609.360	0.999979
5215.353	0.999960	5688.436	0.999987	6200.527	0.999970	6633.995	0.999979
5233.122	0.999983	5731.984	0.999985	6213.644	0.999978	6643.876	0.999988
5242.658	0.999983	5754.881	0.999996	6219.494	0.999981	6678.235	0.999982
5269.723	0.999967	5763.218	0.999997	6230.943	0.999968	6717.940	0.999984

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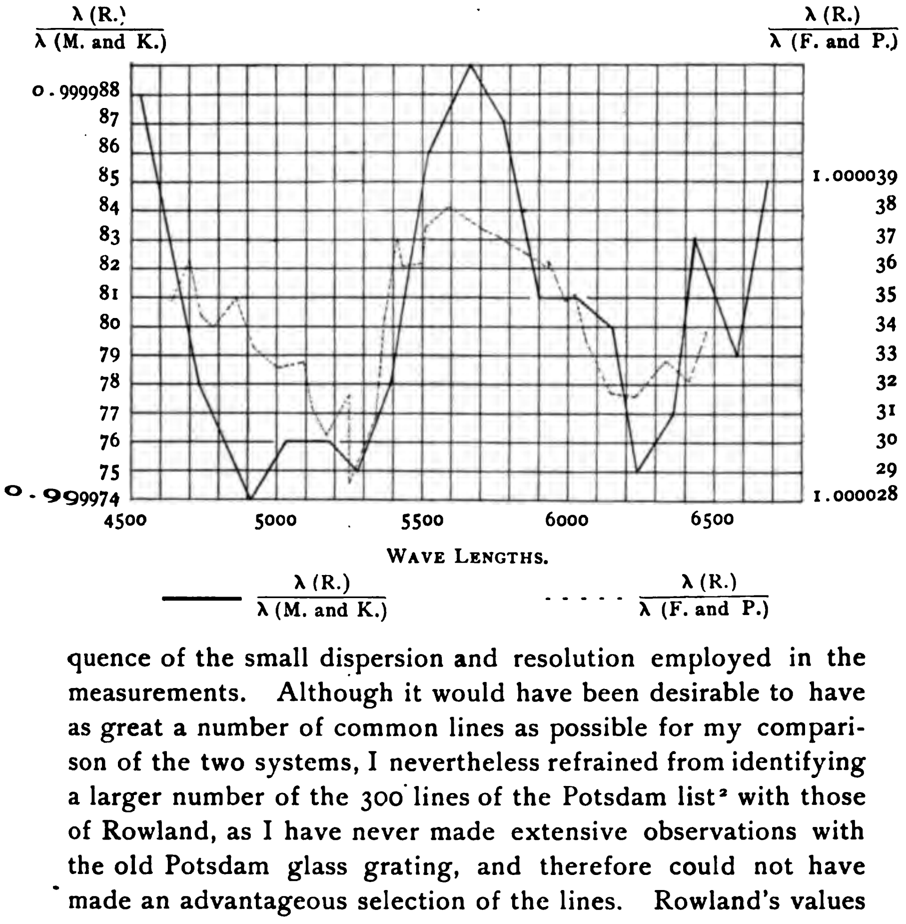
[1] Müller and Kempf give as the probable error of a line on the average ±0.03 tenth-meters (*Publicationen des Astrophys. Obs.*, 8, 145), but it may be seen from the table, pp. 147 ff., that the probable error of a line depends very much upon its character.

I employed as the basis of my computation the list of 127 lines of the Potsdam list of wave-lengths which Müller[1] had already selected in making his comparison of the Potsdam values with Rowland's standards of 1889. Of these 127 lines I omitted, however, 23 more, as the Potsdam values of the line might have been affected by close and often fainter lines, in consequence of the small dispersion and resolution employed in the measurements. Although it would have been desirable to have as great a number of common lines as possible for my comparison of the two systems, I nevertheless refrained from identifying a larger number of the 300 lines of the Potsdam list[2] with those of Rowland, as I have never made extensive observations with the old Potsdam glass grating, and therefore could not have made an advantageous selection of the lines. Rowland's values are of course taken from his "Preliminary Table."



The individual values of the above table exhibit a somewhat irregular behavior, but on plotting on section paper a progres-

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[1] *Ibid.*, 49, 50.

[2] *Ibid.*, 5, 147 ff.

sion is also clearly visible. This becomes more evident on combining into a mean the values of the ratio $\frac{\lambda\,(\text{Rowland})}{\lambda\,(\text{Müller and Kempf})}$ for lines 20 tenth-meters apart. But also in taking this mean still far too few single values are combined in each mean, and I therefore also took means for every 100 tenth-meters, which are represented in the accompanying curve. The close agreement with the curve of Fabry and Perot cannot fail to be recognized, and hence the occurrence of systematic errors in Rowland's table is also evident from the Potsdam determinations of wave-lengths by Müller and Kempf, in the manner first established by Fabry and Perot.

ASTROPHYSIKALISCHES OBSERVATORIUM,
Potsdam, January 3, 1903.

PRELIMINARY NOTE ON SOME MODIFICATIONS OF THE MAGNESIUM LINE AT λ 4481 UNDER DIFFERENT LABORATORY CONDITIONS OF THE SPARK DISCHARGE.

By Sir William Huggins and Lady Huggins.

In his "Note on the Wave-Length of the Magnesium Line at λ 4481"[1] Professor Crew points out that an interesting problem still remains, namely to discover the laboratory conditions under which the line becomes sharp, as in some stellar spectra.

For some years, at intervals, experiments have been made here in the laboratory on the spectrum of magnesium, with the hope of throwing light on the physical conditions of the stellar atmospheres which we may assume to be indicated by the character of this line when present; a line which in the laboratory is subject to a very wide range of modifications, both of character and of intensity.

As it may be some time before these experiments are sufficiently complete for publication, it seems desirable to reproduce at once with this preliminary note, out of the very large number of spectra which have been taken, a few representing the most typical forms of the modifications of this line.

The teaching of these experiments suggests that the condition of the spark-discharge which is most potent in bringing about modifications of this line both in intensity and in character is the greater or less suddenness of the blow of the discharge. To a small extent only does the character of the line appear to be affected by the quantity and the electro-motive force of the electricity which is in action; indeed, such changes as may appear are probably brought about indirectly by the larger mass of material acted upon as the discharge is made more powerful.

The appearance of the line at λ 4481 in the spectrum at the top of the plate may be taken as representing its normal condi-

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[1] Astrophysical Journal, 16, 246, 1902.

tion with capacity in the secondary of the coil. When the jar is taken out of circuit, and the discharge of the secondary takes place directly between the magnesium electrodes, the line becomes thin, defined, and of small intensity, as in spectrum No. 2. In this case the electric blows are less sudden through the incoming of the full self-induction of the coil itself.

The researches of Schuster, Hemsalech, Schenck, Huff, and others have shown that a similar effect follows when the jar-discharge is slowed down by the introduction into the circuit of an independent self-induction. The condition of the line in spectrum No. 3 shows the effect of the introduction of a self-induction, the conditions of the discharge remaining otherwise the same as in photograph No. 1.

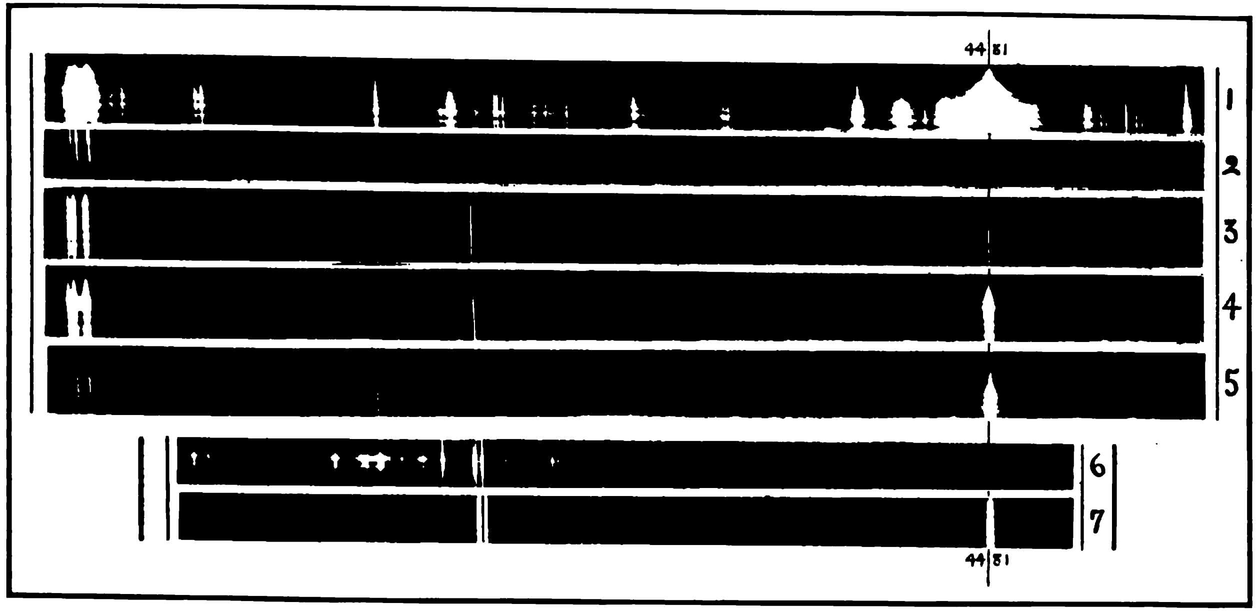
In spectrum No. 5 a stronger alternating current and a capacity four times as great as in No. 1 were employed; but the photograph is feeble from over-exposure. On the contrary, in No. 4 the coil was excited by a feeble continuous current and the capacity in the circuit was reduced to a small jar.

The two spectra placed below were taken some years ago with another spectroscope. They are of interest in showing the great variation of intensity which the line at λ 4481 may undergo without assuming its normal diffused character, as in No. 1. The line in spectrum No. 4 appears to be intermediate in character between that of the line in No. 7 and that in No. 1.

We have still before us the task of the interpretation of the differences in the mode of production of the electric spark, especially as to greater or less suddenness, so as to enable us to connect them with definite conditions of temperature and density of those stellar atmospheres in which the magnesium present absorbs radiations similar in character to those photographed in the laboratory.

London,
January 1, 1903.

PLATE XIV.



Spark Spectra of Magnesium.

ON THE FLAME SPECTRUM OF RADIUM.

By C. RUNGE and J. PRECHT.

DR. GIESEL has recently found that very small quantities of sufficiently pure radium bromide give a characteristic color to the flame of a Bunsen burner.[1] He describes the spectrum on the whole as consisting of two red bands and a bright blue line. In the violet he saw some other less prominent lines.

At the request of Dr. Giesel we have investigated the spectrum more closely, for which purpose he was kind enough to supply us with 13 milligrams of radium bromide of his own making.

To fix the substance on the platinum wire we proceeded in the same way as described by one of us in his paper on the spark spectrum of radium.[2] The platinum wire was doubled up, twisted into a loop, and heated by an electric current. If a fragment of the salt is touched with the glowing wire, it sticks to it, melts, and forms a small drop. When the current is cut off, the drop hardens and begins to give out a bright phosphorescent light. If the wire is again heated, the light ceases at once, but is renewed as soon as the heating is stopped.[3]

The wire carrying a small fragment of the substance was brought into the hottest part of the Bunsen flame, which was placed before the slit of a spectroscope. The spectroscope consisted of a Rowland concave grating of one meter radius. It was mounted in the way described by one of us.[4] If the wire is electrically heated while the substance is in the flame, the intensity of the spectrum is increased, but the substance is consumed more rapidly.

The wave-lengths were read off on a paper scale. The light

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[1] F. GIESEL, *Physikal. Zeitschrift*, 3, 578, 1901–2 and *Ber. d. deutsch. chem. Gesellschaft*, 35, 3608, 1902.

[2] C. RUNGE, "On the Spectrum of Radium," ASTROPHYSICAL JOURNAL, 12, 1.

[3] This phenomenon has already been described by Giesel.

[4] *Wied. Ann.*, 61, 644, 1897.

is not sufficient for a photograph if only small quantities of the salt are at the disposal of the observer.

When the substance is first brought into the flame, there are some lines to be seen, which rapidly lose their intensity, so much so that one must be quick to determine their wave-lengths before they disappear. The blue line at λ 4826 is the last to lose its intensity. It seems to possess the same character as the barium line λ 5536, the strontium line λ4607, and the calcium line λ4226, which are also most prominent when these substances are brought into the Bunsen flame.

In the following table we have noted all we have seen. We believe all the observed lines to be due to radium except the barium line λ5536 and the two sodium lines. The wave-lengths

Wave-Lengths	Remarks	
4405	Weak, diffuse	
4500	Weak, diffuse, observed only once	
4592	Diffuse	
4680	Weak, observed only once, perhaps identical with the strong line of the spark spectrum at λ4682.3	
4718		
4750		
4826	Strong, sharp line, very likely identical with the line at λ4826.1 in the spark spectrum, as Giesel presumes	
509–513	Weak band, observed only once	
5210	Observed only once	
5360	Observed only once	
5535	Impurity, barium λ 5535.7	
5655	Observed only once	
5685	Observed only once	
5890	Impurity, sodium	
5896	Impurity, sodium	
590–605	Weak band	
613–633	Strong band	
6210		These lines are seen in the band, but apparently do not form the band
6216	Observed only once	
6228	Observed only once	
6247		
6250	Observed only once	
6260	Observed only once	
6269		
6285		
6329	Strong	
6349	Strong	
653–670	Strong band	
6653	Strong line; there is a minimum of intensity of the band, in the neighborhood of the line	
6861	Uncertain, observed only once	

of the lines that have been observed clearly and repeatedly we believe to be correct to one or two Ångström units. With those lines, however, which have been observed only once, the error may amount to several Ångström units. The bands have no definite limits. When an ample amount of the salt is brought into the flame, they may appear much broader than we have seen them. It may be that the bands are due to the spectrum of the compound. This might be tested by observing the flame spectrum of the chloride.

HANNOVER,
January 1903.

FIVE STARS WHOSE RADIAL VELOCITIES VARY.

By EDWIN B. FROST and WALTER S. ADAMS.

IN the course of the observations we have been making with the Bruce spectrograph during the past year on stars having spectra of the *Orion* type, the following four stars of this class have been found to vary in respect to their motions in the line of sight, in addition to the three previously announced in this journal (η *Orionis*, *o Persei*, β *Cephei*).[1]

The determinations of velocity so far made are given below. The G. M. T. of the observations is not now communicated, as we do not deem the data at present available to be sufficient for the accurate determination of the orbits of these stars. The number of star lines measured is given for each plate in the fifth column.

δ CETI ($\alpha = 4^h\ 31^m$; $\delta = -0° 6'$; Mag. $= 4.1$)

Plate	Date	Taken by	Velocity	No. of Lines	Measured by
A 291	1901, Nov. 1	F.	+8 km	15	A.
B 227	Nov. 13	F.	+12	10	F.
A 295	Dec. 19	A.	+16	7	A.
A 298	1902, Jan. 4	A.	+6	7	A.
B 383	Aug. 7	F.	+13	8	A.
B 388	Aug. 11	A.	+6	9	A.
B 400	Aug. 27	A.	+9	9	A.
B 404	Sept. 3	A.	+12	8	A.
A 376	Sept. 6	A.	+12	10	A.
A 381	Sept. 7	F.	+6	10	A.
B 432	Oct. 29	A.	+9	8	A.

The spectrum is of Miss Maury's Class IV*a* and has numerous oxygen lines and the usual ones of helium, silicon, hydrogen, and magnesium. The lines are fairly sharp, so that the spectrum is relatively well measurable. The above range of variation in velocity is not large, from +6 to +16 km per sec., but we cannot question its reality.

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[1] ASTROPHYSICAL JOURNAL, 15, 214, 340, 1902; 17, 68, 1903.

ν ERIDANI ($\alpha = 4^h\ 31^m$; $\delta = -3°\ 33'$; Mag. $= 4.1$)

Plate	Date	Taken by	Velocity	No. of Lines	Measured by
B 242	1901, Nov. 20	A.	+12 km	5	A.
B 438	1902, Oct. 30	F.	+28	10	F.
			+26	12	A.
B 443	Oct. 31	A.	+18	7	A.
B 447	Nov. 6	A.	+ 3	8	A.
B 472	Dec. 18	F.	+12	8	F.
B 494	1903, Feb. 5	A.	+25	7	F.

The spectrum resembles that of δ *Ceti*, but the lines are more difficult to measure. The range so far observed is 24 km.

π^5 *ORIONIS* ($\alpha = 4^h\ 49^m$; $\delta = +2°\ 17'$; Mag. $= 3.9$)

Plate	Date	Taken by	Velocity	Number of Lines	Measured by
A 332	1902, March 4	A.	+ 1	3	A.
B 469	Dec. 17	A.	+ 58	5	A.
B 475	Dec. 31	A.	+ 70	5	A.
			+ 72	6	F.
B 480	1903, Jan. 1	Ellerman	+ 32	4	A.
A 384	Jan. 16	A.	+ 7	6	A.
B 488	Jan. 21	F.	− 35	4	A.
			− 32	4	F.
A 390	Jan. 22	A.	+ 73	4	A.

The spectrum of this star is not well adapted for accurate measurement, the lines being broad and very diffuse. A few oxygen lines are present, but they are faint and difficult to set upon. The period is evidently short.

ζ *TAURI.*

The spectrum of the star is peculiar, as has been noted by Lockyer and probably by others. The conspicuous feature in the region of spectrum covered by our plates is the remarkable sharpness and intensity of $H\gamma$. Settings can be made upon this line with such accordance that the radial velocity determined from this line alone is probably not much less reliable than that based on several lines in the case of most other stars of the *Orion* type. Other lines are faintly discernible in the spectrum, chiefly the enhanced lines of titanium and iron. These lines are in general so faint and broad, however, that they have commonly not been employed in the determination of the star's motion.

ζ *TAURI* ($\alpha = 5^h\ 32^m$; $\delta = +21^\circ\ 5'$; Mag. = 3.0).

Plate	Date	Taken by	Velocity	Number of Lines	Measured by
B 219	1901, Nov. 8	A.	+ 17 + 16	1 1	A. F.
A 317	1902, Feb. 12	A.	+ 23 + 24	1 1	A. F.
B 332	April 23	F.	+ 15 + 11	1 1	A. F.
B 410	Sept. 13	A.	+ 18	6	A.
B 425	Oct. 15	A.	+ 34	1	A.
B 440	Oct. 30	F.	+ 31 + 28	1 2	A. F.
B 452	Nov. 6	A.	+ 19 + 21	1 1	A. F.
B 462	Nov. 19	A.	+ 14	1	A.
B 470	Dec. 17	A.	+ 7	1	A.
B 473	Dec 18	F.	+ 9	1	F.
B 476	Dec. 31	A.	+ 4	1	A.
B 482	1903, Jan. 8	A.	+ 2	1	A.
B 485	Jan. 9	A.	+ 5	1	A.
A 386	Jan. 16	A.	+ 4	1	A.

The period is probably rather long. Plate B 452 of the above series is underexposed, and the value derived from it is somewhat uncertain.

η *VIRGINIS* ($\alpha = 12^h\ 15^m$; $\delta = -0^\circ\ 7'$; Mag. = 4.1).

This star has a composite spectrum, both components belonging to Vogel's type I*a* 2, or Miss Maury's VIII*a*. On account of the weakness of the lines of the fainter component the discussion of the star's motion will be based mainly upon the absolute velocity of the brighter component. The binary character of the star was established by the first plate, taken and measured by A.

Plate	Date	Taken by	BRIGHTER COMPONENT		FAINTER COMPONENT		Measured by
			Velocity	No. of Lines	Velocity	No. of Lines	
A 388	1903, Jan. 16	A.	− 31.5	14	+ 42	4	A.
B 493	Feb. 4	F.	+ 0.7 + 0.2	16 15	+ 60 + 63	4 6	F. A.
A 399	Feb. 5	A.	+ 3.4	16	..	..	A.

NOTE ADDED FEBRUARY 18, 1903.

When it was decided to publish at this time the observations of the above stars, we expected also to include the *Orion* type star π^4 *Orionis*, the first two plates of which indicated a range of variation of about 15 km. It was, however, withheld until we should obtain additional plates, as the third and fourth plates gave results nearly like that of the second. We see today in the *Publications of the Astronomical Society of the Pacific* (**15**, 20, 1903) a notice by Dr. H. M. Reese, stating that spectrograms of this star, taken with the Mills spectrograph of the Lick Observatory, on October 6, 1902, and January 4 and 12, 1903, yielded values respectively of + 43, ± 0, and + 6 km. per second.

There is accordingly no reason for longer withholding our observations, which are as follows:

π^4 *ORIONIS* ($\alpha = 4^h\ 46^m$; $\delta = +5°\ 26'$; Mag. 4.0)

Plate	Date	Taken by	Velocity	Number of Lines	Measured by
A 332	1902, March 4	A.	+ 13 km	8	A.
B 466	Nov. 27	F.	− 2 − 1	5 7	F. A.
B 468	Dec. 17	A.	+ 1	6	F.
A 389	1903, Jan. 22	F.	+ 3 + 0	7 6	F. A,

YERKES OBSERVATORY,
February 8, 1903.

SECOND NOTE ON THE SPARK SPECTRUM OF IRON IN LIQUIDS AND COMPRESSED GASES.

By GEORGE E. HALE and NORTON A. KENT.

IN a note published a year ago[1] it was shown that the position and the reversal phenomena of the lines in the spectrum of a spark between iron poles in liquids depend upon a variety of circumstances, chief among which are the electrical constants of the circuit and the nature of the liquid. It was also stated that certain lines in the blue part of the spectrum of iron had been photographed in air at pressures ranging from 1 to 20 atmospheres, and that the shifts of the lines were (approximately) directly proportional to the pressure, thus confirming and extending the results previously found by Humphreys and Mohler for the low potential discharge in air at pressures up to 14½ atmospheres. It was at the same time remarked that the lines thus investigated in air showed none of the peculiar phenomena of reversal which had been observed in the case of the high potential discharge in liquids.

Since this first note was written, the investigation of the spectrum of iron in liquids has been completed. The reversal phenomena previously studied with low dispersion have been photographed with a concave grating of ten feet (3.05 m) radius, on a scale sufficiently great to permit the displacements of the best lines to be measured with errors not often exceeding 0.01 tenth-meter. In the note referred to above it was stated that the preliminary experiments on the effect of self-induction in the discharge circuit were inconclusive. With a coil afterwards constructed, in which the self-induction can be varied from 0.000042 to 0.000426 henry in five steps, change of self-induction has been found to produce more marked effects than change of capacity, length of spark, diameter of terminals, physical or chemical properties of the liquid, or any other variable previously shown to influence the reversal phenomena. Accordingly,

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[1] GEORGE E. HALE, "Note on the Spark Spectrum of Iron in Liquids and in Air at High Pressures," ASTROPHYSICAL JOURNAL, 15, 132, 1902.

changes of self-induction in the discharge circuit have been employed to produce a series of spectra, which pass by gradual degrees from a spectrum consisting almost wholly of bright lines (highest self-induction), resembling that of the iron spark in air at atmospheric pressure, to a spectrum consisting for the most part of dark lines (no self-induction) in the region λ3550–λ4500. Such a series of spectra, if photographed with low dispersion, would closely resemble the spectra reproduced in Plate XI of the note referred to above. A careful series of measures of the lines has shown that as the self-induction is decreased the bright lines move gradually toward the red, while the absorption lines, which begin to appear in the earliest stages, may at first have some apparent shift[1] toward the violet, though later they may be displaced one or two hundredths of a tenth-meter toward the red, rarely more. Full details of the measurements will be given in a paper which will appear soon in the *Publications of the Yerkes Observatory.*

In his paper "On the Interpretation of the Typical Spectrum of the New Stars,"[2] Professor Wilsing describes his experiments on the spectrum of high potential discharges between metallic poles in water, and bases an explanation of the characteristic pairs of bright and dark lines in the spectra of temporary stars upon the phenomena he observed. Wilsing concludes that the pressure resulting from the spark discharge in liquids amounts to several hundred atmospheres. As our own investigations led us to the belief that the pressure, at least in the case of our iron spark, was in reality much lower, we thought it desirable to extend our earlier work on spark spectra in air at high pressures to the more refrangible region studied in the case of liquids. As the apparatus used for such work a year ago proved inadequate, new apparatus has been constructed in the Observatory instrument shop, and with this we have had no difficulty in photographing the spectrum of the iron spark in gases at pressures ranging from 1 to 53 atmospheres. The present note contains a preliminary account of the results hitherto obtained, but many

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[1] Doubtless due in part to the displacement of the lines of the comparison spectrum, caused by pressure in the condensed spark.

[2] ASTROPHYSICAL JOURNAL, 10, 113, 1899.

details must be reserved for the more complete paper which is to appear in the Observatory *Publications.*

In the recent experiments the spark between iron terminals has been observed through a glass window, in the side of a steel chamber provided with a pressure gauge, and connected by means of a heavy copper tube with a steel reservoir containing compressed air or liquid carbon dioxide. The terminals enter the steel pressure chamber through long cylinders of ebonite, and special precautions have been taken to insure the most perfect insulation. The spark is produced by means of a transformer giving about 15,000 volts on open circuit, ordinarily used with a condenser of 0.0066 microfarad capacity, connected with the secondary terminals. In order to insure successful operation of the spark at high pressures, an air break is essential in the discharge circuit. The photographs of spectra reproduced in Plate XV were made in the first order of a concave grating of ten feet radius, ruled with 14,438 lines to the inch (5684 to the cm).

As stated above, the spectra photographed a year ago at high pressures did not extend into the ultra-violet. In a previous note[4] it has been shown that the reversals of the lines in the case of spark spectra in liquids first appear in the ultra-violet, and advance gradually toward the less refrangible region as the conditions for reversal become more favorable. A similar result was shown many years ago by Liveing and Dewar to obtain in the case of arc reversals. It is for this reason that the phenomena described in the present note were not encountered by us in our earlier work at lower pressures on the less refrangible region of the spectrum of the iron spark in air. Nevertheless, we were somewhat surprised to find, in our first test of the new apparatus, that at an air pressure of 14 atmospheres the reversal phenomena in the region $\lambda 3550$–$\lambda 4500$ closely resembled those we were accustomed to photograph in the case of the iron spark in water with but little self-induction in the discharge circuit. It was at once evident that a series of photographs made at different air

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[4] GEORGE E. HALE, "Selective Absorption as a Function of Wave-Length," ASTROPHYSICAL JOURNAL, 15, 227, 1902.

pressures would resemble the series previously obtained with the spark in water by varying the self-induction. Photographs have now been made at pressures ranging from 1 to 53 atmospheres, portions of which are reproduced in Plate XV. In the temporary absence of compressed air at pressures greater than 14 atmospheres, liquid carbon dioxide was used to give higher pressures. It has since been found, however, that at a given pressure the reversal phenomena are more marked in an atmosphere of air than in one of carbon dioxide. This result will render necessary an investigation of the effect of other gases. It has also been found that changes of self-induction in the condenser circuit affect the reversal phenomena in the same sense as in the case of the spark in water, but over a much smaller range.

An examination of Plate XV will show that the phenomena closely resemble those previously described in the case of liquids. At an air pressure of three atmospheres the lines are for the most part bright, though a few cases of reversal appear. It will be noticed that a few of the lines have at this stage increased very markedly in relative intensity. Such lines, as the subsequent photographs show, pass through a maximum of intensity and afterwards reverse. At a pressure of 7 atmospheres the bright lines are broader and more diffuse, and the absorption lines are becoming prominent. It is evident from inspection that many of the reversals are not symmetrical, the bright line being relatively displaced toward the red. At a pressure of 14 atmospheres the dark lines have become very conspicuous, and many of the bright lines have almost disappeared. Some evidences of a continuous spectrum begin to appear at this pressure. At 27 atmospheres (in carbon dioxide) the continuous spectrum is quite conspicuous. The absorption lines are strong and the bright lines are much fainter than before. At 53 atmospheres (also in carbon dioxide) the bright lines have practically disappeared and the dark lines remain, broad and diffuse, on a background of bright continuous spectrum. At this pressure most of those lines whose intensity is increased at moderate pressures are reversed, and the relative intensities of all the dark lines closely resemble those of the bright lines in the spectrum of the iron spark at atmospheric pressure. Even at the highest pressures very few lines less refrangible than λ 4415 are reversed. In the region λ 4800–λ 4900 there are several strong lines unsymmetrically broadened in carbon dioxide at 53 atmospheres, and similarly affected in water. It seems to be true that the order in which various lines reverse is not precisely the same in gases as in liquids.

A careful study of the shifts of the bright and dark lines at these various pressures has brought out certain facts, which are of interest in connection with the results obtained by Humphreys and Mohler on the low potential discharge in air at high pressures, and our own results on the spectra of high potential discharges in liquids. The following tables contain measures of a few lines which may be regarded as fairly typical. Table I gives the shifts of certain lines in the spectrum of a spark between iron poles in water, resulting from changes of self-induction in the discharge circuit. In this series the length of the water spark was 0.3 mm; air spark 10 mm; diameter of terminals (flat ends) in water 2.3 mm; diameter of terminals (rounded ends) in air 4 mm; metal in both cases Bessemer steel; electric fan used to prevent arcing at air gap; distance of terminals below surface of water 56 mm; 15,000 volt transformer; capacity in discharge circuit 0.0066 microfarad. The shifts of the lines toward the red are expressed in tenth-meters, and are positive unless otherwise indicated. The types of the lines, as indicated below, are given in parentheses.

(1) = narrow emission line.

(2) = broad symmetrical emission line.

(3) = broad emission line, diffuse toward red.

(4) = symmetrical absorption line.

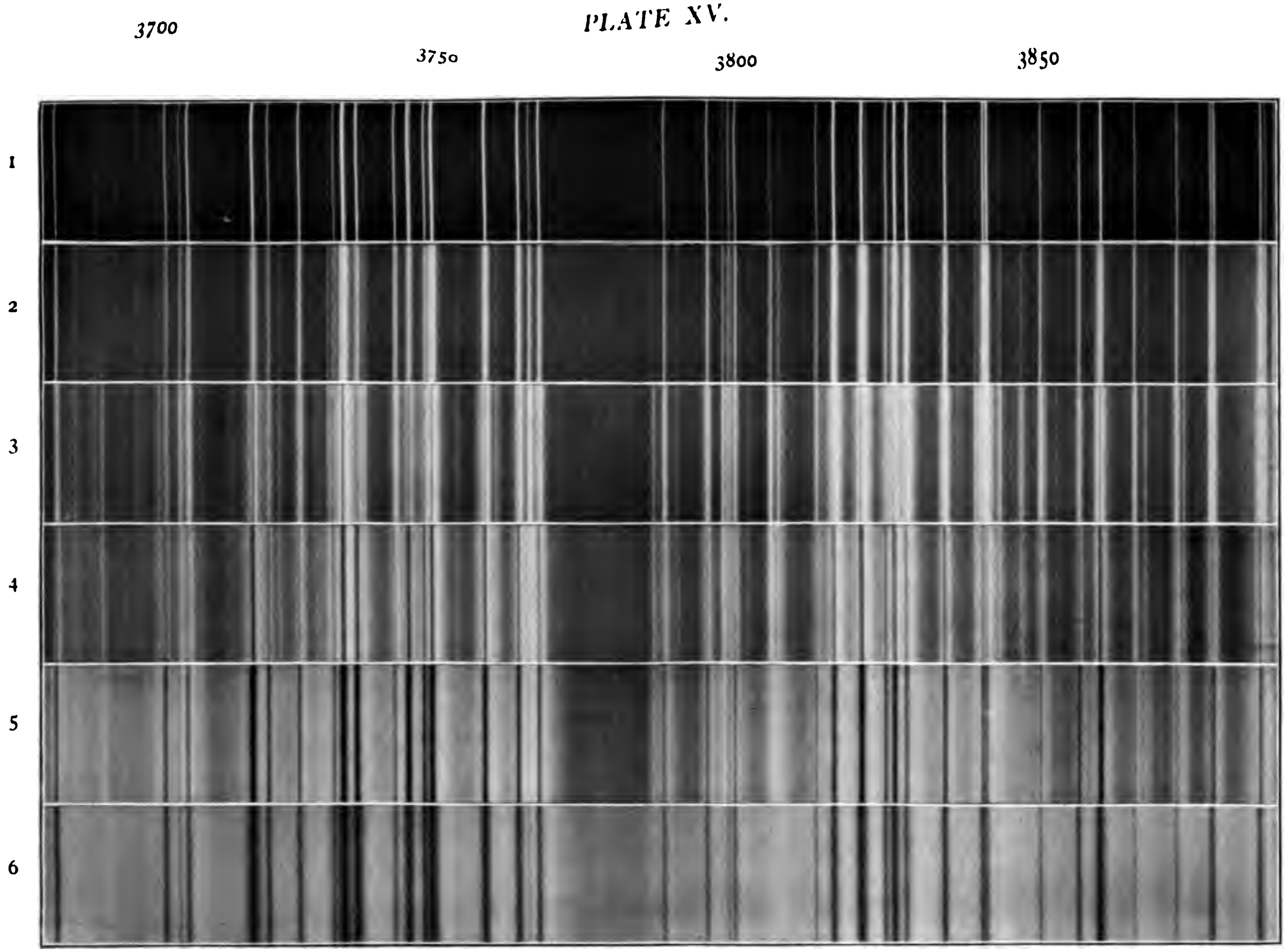
(5) = absorption line superposed symmetrically on broad emission line.

(6) = absorption line superposed on broad emission line, which is strongest on red side.

(7) = similar to (6), but with violet component of bright line lacking.

E signifies that the measured shift refers to an emission line, *A* that it refers to an absorption line. In lines of types (6) and (7) both the emission and absorption components may be measured. In such a case the measurement of the red component (the violet component is not measured) of the emission line does

PLATE XV.



PHOTOGRAPHS OF THE SPARK SPECTRUM OF IRON IN COMPRESSED GASES.

1. In air at atmospheric pressure.
2. In air at 3 atmospheres.
3. In air at 7 atmospheres.
4. In air at 14 atmospheres.
5. In CO_2 at 27 atmospheres.
6. In CO_2 at 53 atmospheres.

not give the true shift of the line, since the setting is made at the center of that part of the line which lies on the red side of the absorption line. Such measures are given here incidentally only because of their previous use by Wilsing.

TABLE I.

IRON SPARK IN WATER.

Shifts corresponding to changes of self-induction in discharge circuit.

Plate Number		659	651	650	658	666	665
Self-Induction Henries		0.000426	c.000310	0.000161	0.000080	0.000042	0.0
Wave-Length	Intensity						
		t. m.	*t. m.*	*t. m.*	*t. m.*	*t. m.*	*t. m.*
3606.85	6	(2) 0.01 *E*	(2) 0.02 *E*	(2) 0.04 *E*	(2) 0.08 *E*	(2) 0.14 *E*	(7) -0.01 *A* .28 *E*
3765.70	5	(2) .02 *E*	(2) .03 *E*	(2) .01 *E*	(2) .09 *E*	(2) .10 *E*	(3) .21 *E*
3815.99	9	(3) .05 *E*	(3) .07 *E*	(3) .12 *E*	(6) .00 *A*	(6) .01 *A*	(6) .03 *A*
3827.98	9	(3) .02 *E*	(3) .05 *E*	(2) .09 *E*	(7) - .01 *A* .35 *E*	(6) .00 *A*	(4) .02 *A*
4063.75	10	(2) .03 *E*	(2) .02 *E*	(2) .04 *E*	(6) .06 *A*	(6) .02 *A*	(4) .02 *A*
4294.32	6	(2) .02 *E*	(2) .02 *E*	....	(2) .02 *E*	(2) .06 *E*	....
4308.06	10	(2) .02 *E*	(3) .05 *E*	(2) .06 *E*	(6) - .05 *A*	(6) - .01 *A*	(6) .02 *A*
4325.94	10	(3) .02 *E*	(3) .04 *E*	(2) .03 *E*	(6) - .01 *A*	(6) - .03 *A*	(6) .01 *A*

TABLE II.

IRON SPARK IN AIR AND CO_2.

Shifts corresponding to pressures ranging from 3 to 53 atmospheres.

Plate Number		842	839	833	853	852
Pressure in Atmospheres		Air 3	Air 7	Air 14	CO_2 27	CO_2 53
Wave-Length	Intensity					
		t. m.	*t. m.*	*t. m.*	*t. m.*	*t. m.*
3606.85	6	(2) 0.06 *E*	(2) 0.14 *E*	(7) 0.05 *A* .39 *E*	(4) 0.05 *A*	(4) 0.12 *A*
3765.70	5	(2) .09 *E*	(2) .15 *E*	(7) .05 *A* .33 *E*	(4) .07 *A*	(4) .12 *A*
3815.99	9	(6) .04 *A*	(6) .05 *A*	(6) .08 *A*	(4) .08 *A*	(4) .14 *A*
3827.98	9	(2) .11 *E*	(6) .06 *A*	(6) .10 *A*	(6) .07 *A*	(4) .20 *A*
4063.75	10	(2) .07 *E*	(5) .06 *A*	(5) .07 *A*	(5) .10 *A*	(5) .18 *A*
4294.32	6	(2) .04 *E*	(2) .09 *E*	(2) .16 *E*	(2) .21 *E*	....
4308.06	10	(2) .09 *E*	(5) .08 *A*	(5) .09 *A*	(5) .12 *A*	(5) .18 *A*
4325.94	10	(2) .07 *E*	(5) .04 *A*	(5) .10 *A*	(5) .09 *A*	(5) .22 *A*

Table II contains the shifts of the same lines as observed at pressures of 3, 7, and 14 atmospheres in air, and at 27 and 53 atmospheres in carbon dioxide. The constants of the circuit were the same as in the case of water, except that the external air gap was 5 mm long.

As Humphreys and Mohler have shown, the reversals in the case of the arc in air at high pressures are generally symmetrical, the absorption lines being displaced toward the red equally with the emission lines. In the case of the spark in water we have found, as the table shows, that the absorption lines are but little displaced toward the red, though they sometimes have a small apparent displacement toward the violet. The emission lines, however, are considerably displaced toward the red, and this displacement increases as the self-induction in the discharge circuit decreases. A knowledge of the true displacement of the bright lines is obtained from a study of those lines which do not reverse before the last stages of the process are reached. Thus the errors resulting from the presence of the absorption lines are avoided. At moderate pressures the absorption lines are displaced less than the bright lines, though their displacements are considerably greater than in the spectrum of the spark in liquids.

These are only a few of the lines which we have already measured, but much additional material will be required before the results can be discussed satisfactorily. It may be noted, however, that the relative shifts of several lines in air and water indicate that the pressure produced by our iron spark in water (no self-induction in the discharge circuit) is much less than Wilsing's value of several hundred atmospheres. An extension to high pressures of the law connecting pressure and displacement will be possible as soon as a complete series of spectra has been obtained in a single gas. But on account of the lack of agreement among the shifts obtained for different lines, and the possibility that in the high potential discharge the pressure of the gas is not the sole controlling factor, it is hoped that the present work may be supplemented by an investigation of the discharge at potentials ranging from 110 volts to 15,000 volts.

YERKES OBSERVATORY,
February 11, 1903.

Minor Contributions and Notes.

REPLY TO E. VON OPPOLZER'S REMARKS ON BIGELOW'S "ECLIPSE METEOROLOGY."[1]

On p. 738 of *Astronomy and Astro-Physics*, **12**, 1893, E. von Oppolzer writes: "Assuming that the solar atmosphere is made up of hydrogen, the diminution of temperature per second [$1'' = 720860$ m] is $\theta = 13740°$. At a distance of one second above the photosphere, we have, therefore, a prevailing temperature 14000° lower than on the surface of the photosphere." Inasmuch as the prevailing temperature of the photosphere is by general consent in the neighborhood of 7000° C., this statement is so far in error as to discredit the theory upon which the result is based. His description in the note mentioned of the work summarized in my *Eclipse Meteorology*, pp. 77–83, is hopelessly in error, and the reader is referred to my original text. There should be no difference of opinion about the deduction of the formulæ employed, as they follow the lines laid down in my reports, *International Cloud Observations*, 1898, pp. 487–490, or *Barometry of the United States*, 1902, chap. 2, which is common meteorology. Since the height of a homogeneous atmosphere on the Sun has a fundamental bearing in the studies of the pressures and temperatures of the solar atmosphere, it may be proper to deduce this constant again, and to explain the terms that enter into it. A homogeneous atmosphere is one which has throughout its length a constant mass per unit volume, this mass being that of the lowest cubic volume of the gas composing the atmosphere itself, and the total pressure being that of the actual atmosphere. In the case of the Earth this pressure is, in units of weight,

$$p = \sigma_m B_n = 13595.8 \times 0.760 \quad \text{in kilograms/meter}^2,$$
$$= \sigma_o l \quad = 1.29305 \times 7991.04,$$

where σ_m, σ_o are the weights of the unit volume of mercury and air, and B_n, l the heights of the homogeneous columns, respectively.

Similarly the terms may be computed for a hydrogen atmosphere on the Sun, as follows: To deduce the mass of the unit volume at the

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[1] ASTROPHYSICAL JOURNAL, **16**, 334, 1902.

Sun from the terrestrial constants, we must take the pressure and temperature of the Sun's photosphere. Gravity is $g = 27.6\, g_o$, and the temperature I have assumed to be $7535° = 27.6 \times 273$, or $T = 27.6 T_o$. There are two reasons for using $T = 7535°$C.: (1) The computed temperature of the solar surface hovers around 7000°C., while the figure 7535 "serves to systematize the solar and terrestrial constants, for hydrogen and air respectively, in a single numerical scheme," as given on p. 77. (2) The observed ordinates of the normal solar spectrum, from Professor Langley's results, in the region of the wave-lengths $1.5\,\mu$ to $1.7\,\mu$ are longer than correspond to radiation temperatures of less than $T = 7535°$. There seem to be certain waves which pass through both the solar and terrestrial envelopes without depletion, and which will not match any lower temperature curves. This is shown in the *Monthly Weather Reviews* December 1902. Taking the usual notation, Earth $(P_o, T_o, \sigma_o, g_o)$, Sun (P, T, σ, g), we have

$$P_o = g_o \sigma_m B_n \qquad \text{for the Earth,}$$

and

$$P = 27.6\, g_o \sigma_m B_n \quad \text{for the Sun.}$$

Since the density varies by the formula,

$$\sigma = \sigma_o \frac{P}{P_o} \frac{T_o}{T} = \sigma_o \frac{27.6\, P_o}{P_o} \cdot \frac{T_o}{27.6\, T_o} = \sigma_o \,,$$

it is inferred that we can use the terrestrial densities on the Sun for the temperature $T = 7535°$, and thus unify the two systems in one numerical scheme. It is evident that I have not omitted the gravity factor in $g = n \,.\, g_o$, as von Oppolzer stated in his notes.

For the homogeneous atmosphere of hydrogen we have, by the thermodynamic and the dynamic formulæ, respectively,

$$l = RT = 420.552 \times 7535 = 3168860 \text{ m} \,,$$

and

$$l = \frac{\sigma_m B_n \times 27.6}{\sigma_n} = \frac{13595.8 \times .760 \times 27.6}{0.089996} = 3168860 \text{ m} \,.$$

Hence the barometric constant for common logarithms is $K = \frac{l}{M}$ $= 7296570$, as used in my formulæ.

On p. 77 there are numerous checks by cross-computations among the formulæ, and the numbers are consistent with one another. From this point onward the discussion follows well-known lines, and they need not be indicated more fully. My results vary somewhat in detail from Fényi's, but generally agree closely enough to say that we have reached similar conclusions by different methods.

It should be noted that, if a pressure of five atmospheres be assumed for the upper strata of the photosphere, the computed diminution of pressure outward seems to be in harmony with the observed extent of the inner corona. Also, from these data one may compute the pressures on the inner strata below the surface of the photosphere, assuming the structure to be arranged practically in adiabatic layers, and thus construct an approximate solar meteorological system. It is very desirable to determine whether this use of the temperature $T = 7535^\circ$ is not permissible from the observational data. It would make the solar constant at the Earth about 4.0 gram-calories per minute, and there are reasons for thinking it is higher than 3.0 gram-calories. Indeed, there are several directions in which these constants can be utilized, unless my suggestion meets with well considered objections.

FRANK H. BIGELOW.

WEATHER BUREAU,
January 5, 1903.

CORRECTION.

IN the December number, p. 337, of the ASTROPHYSICAL JOURNAL, the visual rediscovery of *Eros* last August at the Chamberlin Observatory of the University of Denver was attributed to me. The rediscovery was really made by Dr. Charles J. Ling, to whom the credit is due.

HERBERT A. HOWE.

ERRATA.

ASTROPHYSICAL JOURNAL, Vol. 16, November 1902:

Page 189, third line from foot, *for* 63300, *read* 63300π.
190, fourth line from foot, *for* r, *read* z.
190, fourth line from foot, *for* γ, *read* γ^2.
190, last line, *for* (m^2-n^2), *read* $(m^2-n^2)^2$.
191, sixth line from top, *for* zcn, *read* $2cn$.

Vol. 16, December 1902:

In equation (23) the first term within the bracket $= D$, should be written $\frac{3}{2}\rho$ instead of ρ and the second term should be $\frac{\rho^2}{u}$ instead of ρ.

In the three equations following (31) *for* $\theta_{\max} = 2^\circ\ 20'$ and $\theta_{\max} = 6^\circ$, *read* $\theta_{\max} = 0^\circ.22$ and $\theta_{\max} = 0^\circ.6$ respectively.

Vol. 17, No. 1, January 1903:

Plate I, exchange $-15'$ and $+15'$.
III, *for* Light Curve, *read* Velocity Curve.

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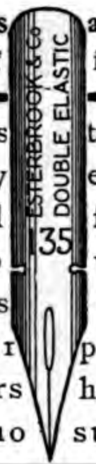
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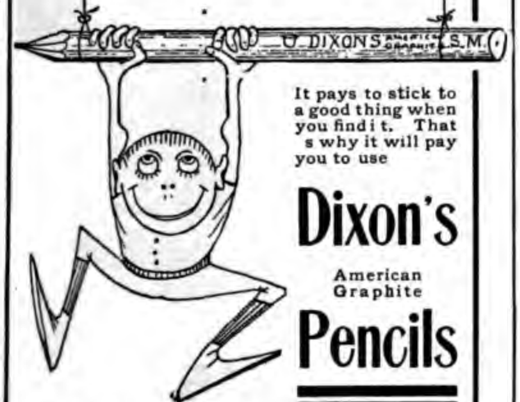
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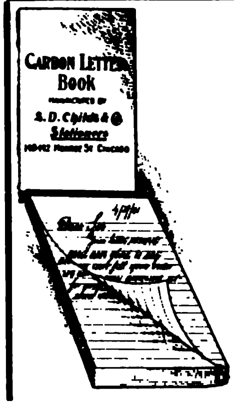
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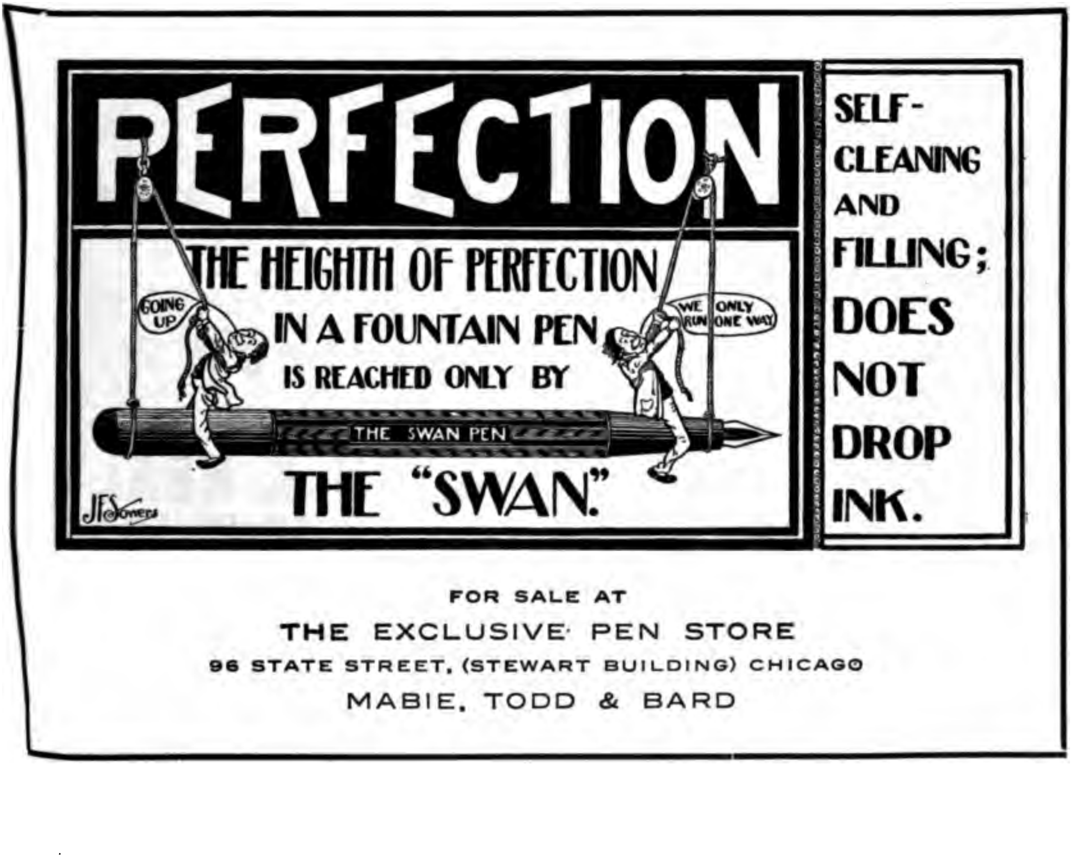
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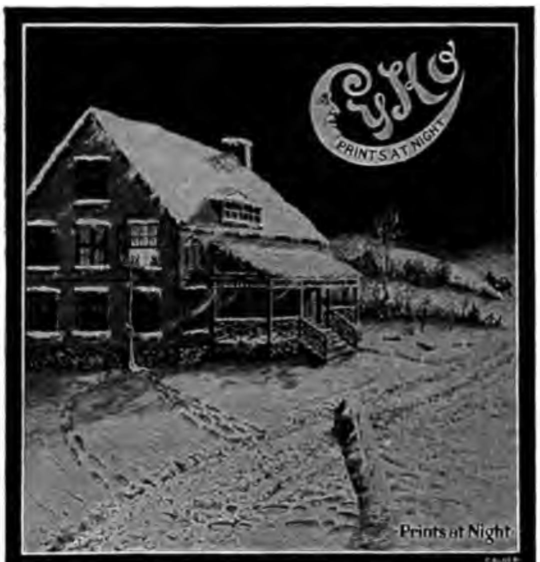
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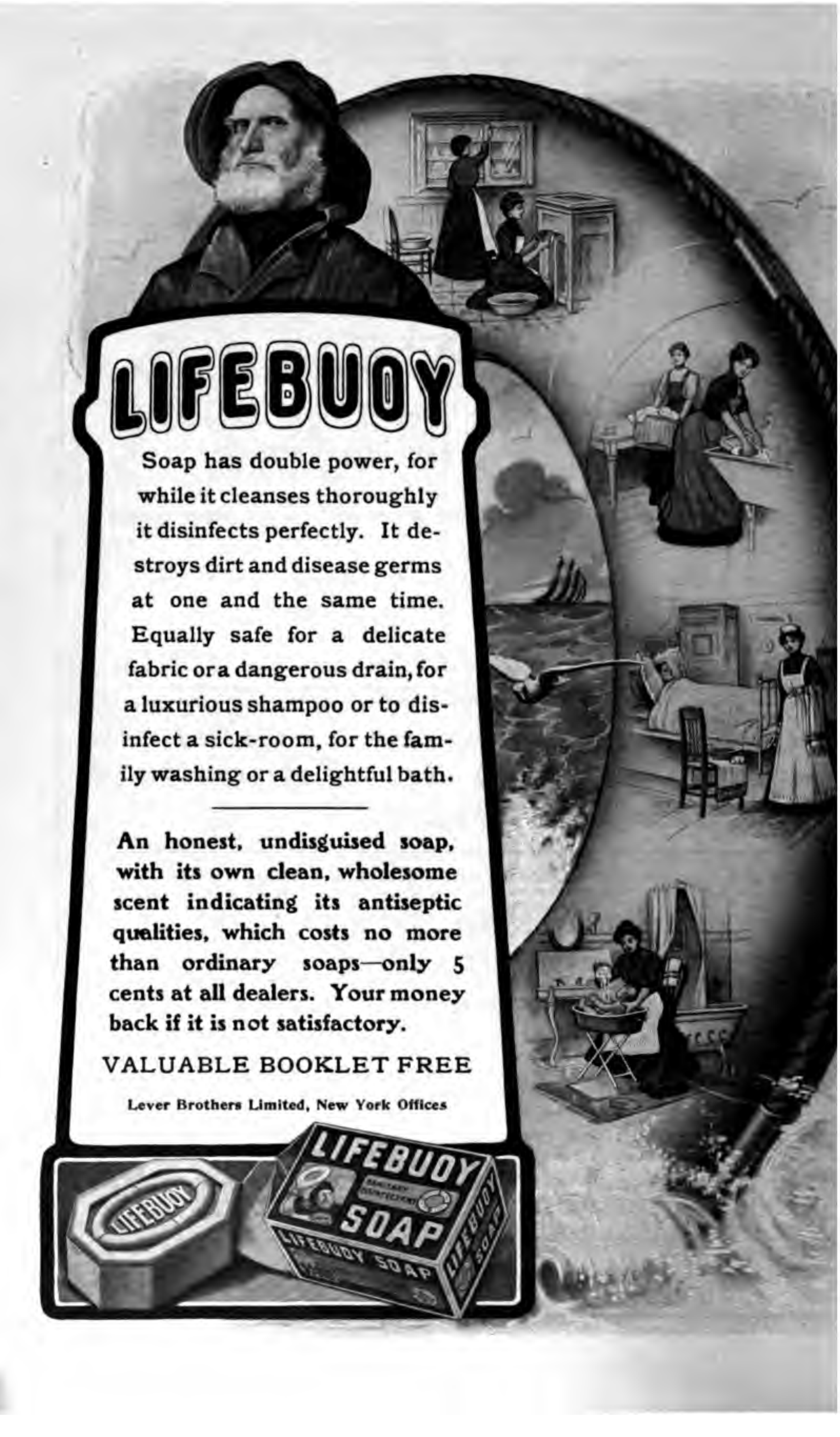
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VOLUME XVII NUMBER 3

THE ASTROPHYSICAL JOURNAL

An International Review of Spectroscopy and Astronomical Physics

EDITED BY
GEORGE E. HALE AND EDWIN B. FROST
of the Yerkes Observatory

APRIL 1903

CONTENTS

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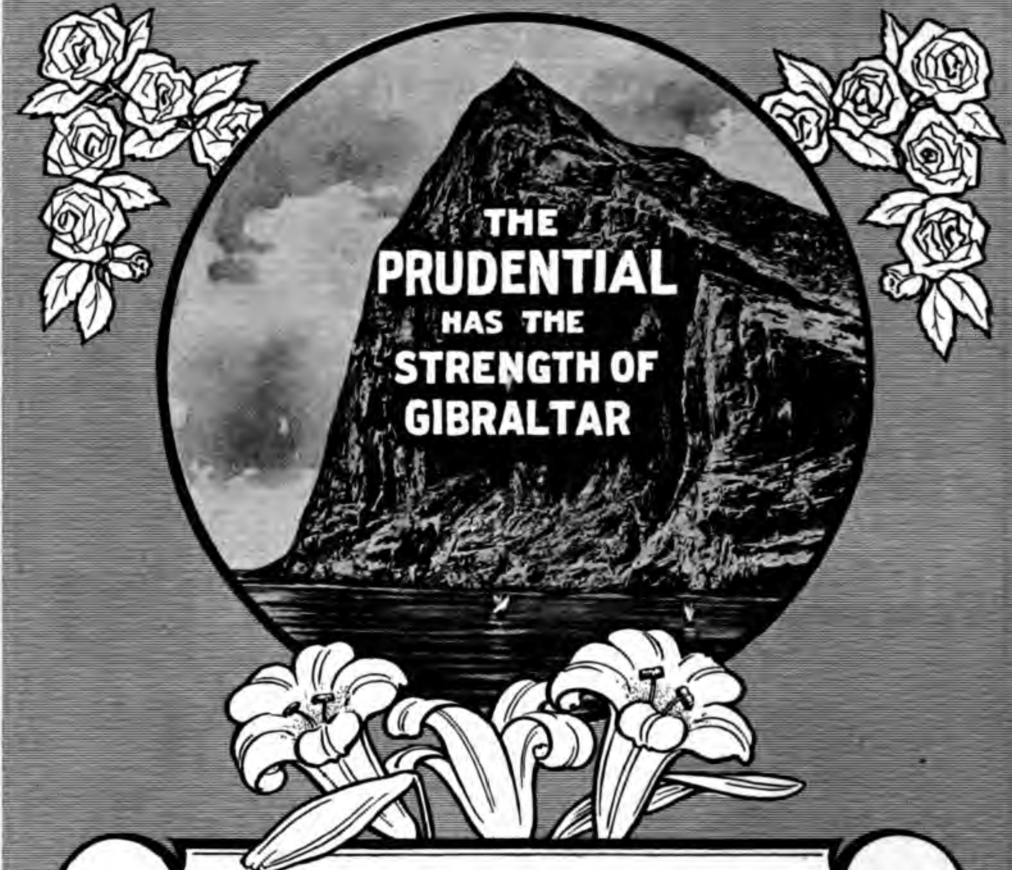
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THE
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AND ASTRONOMICAL PHYSICS

VOLUME XVII APRIL 1903 NUMBER 3

THE EVOLUTION OF SOLAR STARS.[1]

By ARTHUR SCHUSTER.

THE contemplation of our solar system, in which a number of planets move around the Sun in the same direction, and nearly the same plane, gave rise to the idea that our Sun has gradually condensed from a nebulous mass. This idea was confirmed by the discoveries of the telescope, which enabled men to see nebulous masses suspended in the sky, some spread out irregularly, some in spiral forms with denser portions, and some of globular shape, with a starlike nucleus in the center. It was clearly a tempting subject to astronomers and others to speculate on the gradual formation of the stars out of the original nebulous chaos. No wonder, then, that the interest which had been aroused by Kant and Laplace, when they formed their celebrated Nebular Hypothesis, has been growing steadily, especially since the spectroscope gave us the means of studying the material out of which the stars are formed.

The readers of this JOURNAL must all be familiar with the main facts of stellar spectroscopy and the general idea of stellar

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[1] Read before the *Royal Philosophical Society of Glasgow*, November 6, 1901. Revised for publication in the ASTROPHYSICAL JOURNAL, January 1903.

evolution which these facts have suggested. Everyone recognizes that some kind of evolution is clearly indicated by the manner in which star spectra classify themselves into groups which, though distinct, are yet connected with each other by intermediate types. But while agreeing on a general process of evolution, there is still a good deal of room for differences of opinion on the life-histories of particular stars. One of the important questions which may be raised is this: Does each star or, at any rate, the great majority of them, pass through each of the stages of a uniform evolution? Has, for instance, our Sun at one time given a spectrum identical with that of α *Leonis?* Further, are we justified in concluding that all stars are made up of the same chemical elements in the same proportion? And lastly, admitting a uniform evolution, what is the meaning, as the star grows older, of the gradual displacement of the hydrogen in its atmosphere, first by calcium, and ultimately by iron and other metals?

Before we enter into a fuller discussion of these points, I shall briefly review the methods of experimental investigation which are at our disposal. The simple spectroscopic analysis, which only tells us of the presence of an element, is now complicated, but improved, by the observed fact that spectra are found to vary according to the experimental conditions. If we volatilize a metal by a powerful spark, it sends out waves which are different from those which are seen with a weak spark; and if we replace the spark by the voltaic arc, which volatilizes more material, but is probably at a lower temperature, or by the oxy-hydrogen flame, distinct differences due to the different condition of the luminous vapor generally appear in the spectra. Opinions are not quite concordant as to the cause of these differences, how far they depend on temperature simply, and how far pressure and density may affect them; or whether, finally, the dissociating power of high electric tension may alone be sufficient to explain the observed facts. The metallic absorption in the solar spectrum seems roughly to correspond to that of our electric arc, while, according to Sir Norman Lockyer, the metallic lines seen in the groups of stars intermediate between the helium and [illegible]ar spectrum, correspond more closely to the spectra observed in our strongest spark discharges.

In addition to the changes which are produced by temperature and density, we have an effect due to pressure, which consists in a slight lengthening of the waves sent out by the molecules. This effect, which was discovered by Messrs. Mohler and Humphreys, allows us to determine that the pressure to which the vapors in the Sun are subjected is somewhere between two and seven atmospheres.

The investigation of thermal radiation forms another avenue through which we may approach the all-important question of the surface temperature of the stars. It is only quite recently that Mr. E. F. Nichols has succeeded in comparing the total heat radiation of some of the brightest stars. *Vega* and *Arcturus* judged by the eye have the same magnitude, which means that the same amount of that radiation which affects our eyes reaches us from each of these two stars. But when measured by an instrument which is sensitive to all radiation, *Arcturus* is found to have more than double the intensity. As the proportion of total radiation to luminous radiation diminishes with rising temperature, this would indicate a lower temperature for *Arcturus*, and confirm the conclusion, arrived at on other grounds, that the hydrogen stars have a higher surface temperature than the solar stars. Without actual measurements, we may derive the same result from an inspection of the ultra-violet region of the spectrum. This region is made up of rays which are too short to affect our retina, but which produce a photographic effect, and ought to be stronger and more extended, the higher the temperature of the radiating body. We find that in general the hydrogen stars are those which are richest in this ultra-violet light.

These different lines of argument, all leading to the same result, justify us in saying that the surface temperature of the hydrogen stars is higher than that of the solar stars. An extension of the same reasoning leads to the belief that the helium stars have a temperature which is higher still.

The outward appearance and internal constitution of the stars is not solely defined by the temperature of their surface, and we are in some cases in possession of important information concerning their size, mass, and density. Doppler's principle has received important applications, and will probably yield further results. It might, *e. g.*, give us some indications whether any star is near the point at which instability sets in owing to centrifugal force.

Were a star to revolve around an axis which does not point toward the Earth, and with sufficient velocity to be near the point at which it could throw off a planet or break up into two stars, we could not fail to notice it by the broadening of its lines; but at present there seems little hope that we shall ever witness so interesting an event as the formation of a double star out of one rotating body.[1] Yet there are several cases of double stars where the two bodies must be nearly in contact with each other, and some of these must have been formed, not so very long ago, by the splitting up of a single rotating mass.

Passing on to the light thrown by theoretical investigations on the constitution of stars and other systems, I must notice in the first place those researches which refer to the internal state of gaseous masses condensing under the action of gravitational forces. A mass of gas sufficiently great to collect into a globular body will be denser at the center than near the surface, because the whole weight of the outer layer will cause pressure, and therefore increased density of the central portions. As regards the temperature, we might suppose, in the first place, that there is no difference throughout the mass; but even if this were the case at any one time, it could not long remain so. If the gas be warmer than the surrounding space, radiation will take place, accompanied necessarily by a lowering of temperature in some parts, and consequently the setting up of ascending or descending convection currents. These convection currents will ultimately establish a distribution of temperature which is

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[1] (Note added February 1903.) Is it possible that the phenomena of so-called new stars may be due to the sudden violent disturbance produced by the formation of a double star? In such a splitting up, gases which are enormously hotter than the surface gases must suddenly be brought to the surface.

not uniform, and has been named by Lord Kelvin the "convective equilibrium."

If a star is a mass of gas in a state of convective equilibrium, its temperature must increase downward. The rate of increase depends to a great extent on the internal constitution of the molecules. At places where the gravitational attraction is the same, the increase of temperature with depth is proportional to the molecular weight multiplied by a number which is 0.4 in the case of gases like mercury vapor, containing one atom in each molecule, and about 0.3 in the case of gases which contain two atoms in a molecule. But as it is exceedingly likely that at the temperature of the stars all molecules are monatomic like mercury vapor, we may base our calculations on that assumption. The investigations of Homer Lane, Ritter, and Lord Kelvin allow us to solve the problem of the distribution of temperature and density within a star, assuming the interior to behave like a perfect gas in a state of convective equilibrium. Lane was the first to see the importance of a conclusion, which may appear paradoxical at first sight, but which is based on strict mathematical reasoning. According to him, a star, while it radiates heat into space, does not cool, but actually becomes hotter, and this is due to the fact that the contraction, which accompanies the loss of heat, is accompanied by an evolution of heat which more than compensates for the loss. We may imagine radiation to take place chiefly from the outside, and there would no doubt be a lowering of the temperature in these outer layers, if all convection currents were artificially stopped. But at the same time the contraction of the outer shell, inclosing the deeper layers, would cause a rise in temperature in the inside, and consequently a disturbance of the thermal equilibrium. This could be re-established only by convection currents, which would supply the lost heat to the outer layers. Calculation shows that the temperature of the center of a star increases in the same proportion as the diameter of a star diminishes; but it must be clearly understood that all these conclusions are based on the supposition that the whole mass of the star behaves like a perfect gas, a supposition which fails to be true at the surface of a star, and also near its center, but probably holds very nearly in the intermediate layers.

If a star contained only perfect gases, its surface would be formed where the absolute zero of temperature is reached. But the metallic vapors which to a great extent compose the stars condense into a liquid at a temperature of more than 1,000° above the absolute zero, and we must therefore imagine the boundary of the stars to be formed, not at the zero of temperature, but at the place where a cloud-like condensation of vapors takes place, the temperature of these clouds being probably somewhere between 4,000° and 20,000° C. This formation of clouds, though it precludes us from applying Lane's results to the outer layers of stars, does not affect his calculations as to their internal constitution, which probably give us a good representation of the state of a star from the photosphere down to considerable depths. Ultimately, and especially in the case of stars which are already advanced in their condensation, the equations will fail, because when the molecules of a gas become as near to each other as they are in liquids, molecular forces come into play, which prevent the gases from behaving in the ideal manner of a perfect gas. The molecular forces diminish the compressibility, and ultimately the heat which is generated by compression will fail to compensate for the heat lost by radiation. When that period has been reached the star will begin to cool, pass into the liquid state, and soon cease to be luminous.

The questions which meet us when we try to interpret stellar spectra will be more easily understood after we have examined more closely what happens on the surface of the Sun. We may, in the first place, inquire with advantage whether our knowledge of the constitution of that body supplies us any arguments for or against the theory of convective equilibrium, as presented to us by Lane and Ritter. I have calculated, chiefly from the data supplied by Ritter, the density, the pressure, and the temperature of the inside of a star having the same mass and size as the Sun, and behaving like a perfect gas in a state of convective equilibrium. The numbers are given in the accompanying table.

A simple calculation allows us to extend the results to a period of time when the Sun had a larger diameter. The first column of the table defines the position of the different layers in terms of the fraction obtained by dividing the distance of any layer from the center, by the distance of the uppermost layer. The second column gives the density, and the third the pressure in megadynes per square centimeter, that unit being very nearly equal to our atmosphere. The last column shows the temperature, which depends, however, on the nature of the gas; the numbers given apply to hydrogen, assuming it to retain its biatomic constitution, and should in other cases be multiplied by the molecular weight. Thus assuming the whole of the inside of the Sun to be made up of hydrogen split up into monatomic elements, the temperature at the center would be 12,000,000 degrees. If made up entirely of monatomic iron, the temperature would have fifty-six times that value. To apply the table to a previous period in which the diameter of the Sun was, *e.g.*, twice as great, we should have to divide the second column by 8, which is the cube of 2, the third column by 16, which is the fourth power of 2, and our fourth column by 2. It is a curious fact, which is not perhaps without significance, that the central density of the Sun, as calculated on the assumption of its being a perfect gas, is only very little in excess of the density which, according to the most careful recent estimate, is to be ascribed to the central portion of the Earth, and again that that estimate is very little in excess of the density of solid iron.

GASEOUS SPHERE IN CONVECTIVE EQUILIBRIUM.

Total mass = mass of Sun = 2×10^{33} grams.
a = molecular weight compared to hydrogen.
R = radius of sphere.
= $700{,}000/\beta$ kilometers,
where β is a factor which is equal to unity in the case of the Sun.
r = distance from center.
$x = r/R$.
Mean density = $1.406/\beta^3$.

x	$\beta^3 \times$ Density	$\beta^4 \times$ Pressure in Dynes per Square Centimeter	Temperature
0	8.44	8.65×10^{15}	$24.60 \times 10^6 \times \alpha/\beta$
0.1	8.17	8.19	24.06
0.2	7.39	6.93	22.51
0.3	6.23	5.21	20.07
0.4	4.88	3.47	17.07
0.5	3.54	2.03	13.77
0.6	2.33	1.01	10.43
0.7	1.36	0.41	7.28
0.8	0.65	0.12	4.45
0.9	0.20	0.017	2.02
1.0	0.00	0.00	0.00

If it is allowable to imagine the Sun to consist chiefly of iron vapor, that vapor, when above the so-called critical temperature, might be expected to follow the laws of a gaseous compressibility until the density is nearly equal to that of liquid iron, and, whatever the temperature, we shall not be able to compress gaseous iron to a density greater than that of solid iron. It is also allowable to conclude from this reasoning that the distribution of density in the interior of the Sun is not very much different from that indicated in the table, being probably rather less in the central portions, and hence rather greater in the outer portions of the solar mass.

Though the distribution of density and pressure in the interior of a star is probably fairly well represented by the table, the temperature almost certainly is considerably less through the greater portion of the mass. The failure of our equations in this respect is due to diminished compressibility, and also to our having left all effects of radiation and conduction of heat out of consideration. The effects of conduction will be most marked where, owing to increased density and diminished gravitational attraction, the convection current becomes less effective, as for instance near the center of the star. The effects of radiation will be most marked near the surface, and especially in those portions of the star which lie above the cloudy condensations which we have considered to make up its surface. Gases like hydrogen will reach to some height above the surface, and form an atmosphere around the main body of the star. Were it allowable to neglect radiation altogether, these gases would be in convective equilibrium and rapidly diminish in temperature as they rise above the surface; they could not in fact rise much above the surface before they would be reduced to the zero of temperature.[1] The fall in temperature with altitude above the surface of the Sun is, according to calculation, $26 \times a$ degrees centigrade per kilometer, where a is, as before, the molecular weight. Thus for monatomic iron vapor the diminution in temperature would be 73,000° C. for each 100 kilometers.

It may not be unnecessary to say a few words as to the evidence we possess that the convection currents which play so important a part in the theoretical investigation actually exist in the Sun. The surface radiates an amount of heat into space of which we can form a very fair estimate by measuring the quantity which reaches the Earth. The number so obtained is 1,340,000,000 calories per square meter of the solar surface, the unit of heat being the amount necessary to raise one gram of water through one degree. We obtain an idea of what that number means if we imagine the Sun to be surrounded by a shell of ice; the heat supplied by radiation could melt in each minute a layer of ice fifty-eight feet thick. Or, expressing it with Lord Kelvin in terms of power, we may say that the solar surface does work by radiation equivalent to 131,000 horse-power for each square meter of his surface. The heat thus lost by radiation must be supplied from the inside of the Sun, otherwise the solar surface would cool down in a fraction of a second to a temperature at which it would cease to be luminous. If the heat is carried from the inside to the outside by convection alone, the velocity of the currents of vapor must be very great. Taking the pressure of the vapor near the surface to be one atmosphere, we may say that all the heat contained in a layer having a thick-

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[1] (Note added February 1903.) Unless radiation can by itself alone establish a state of equilibrium, convection currents must still take place, and be the predominant factor in the distribution of temperature. Professor Sampson has tried to establish a state of temperature for the case of radiation alone, but his distribution is unstable. As far as my present results go, radiation cannot seriously affect the temperature distribution in the inside of the Sun, unless the material composing it is very much more transparent than we have a right to expect.

ness of 370 meters is lost by radiation in each second of time, and this number does not depend on the nature of the vapor or on its temperature. A layer of that thickness would have to be replaced by convection in every second if the temperature of the surface is to be maintained. From this I calculate that if the difference in pressure between the descending and ascending currents is one atmosphere, the velocity of the convection currents must be 616 meters per second, or about 1,000 miles per hour. These up-and-down draughts of vapor must take place with the calculated velocity, unless an appreciable portion of the heat is supplied from the inside in some other way, as for instance, by radiation. It is difficult to form an estimate as to how far radiation can help to keep up the temperature of the surface. I have made some calculations on that point which, though they have yielded interesting results, cannot at present be expressed in definite numbers. It is sufficient for the present argument to maintain that, even if radiation takes a prominent part in the determination of the distribution of temperature, we cannot escape the conclusion that convection currents must bring about a continuous interchange of matter between the inside and outside of the Sun. This theoretical conclusion is amply confirmed by observation, as is shown by the violent motion observed in the chromosphere and prominences.

In the solar eclipse which was observed in the West Indies in the year 1896 one of these prominences reached to a distance of 140,000 miles. This is by no means the greatest height that has been observed, a prominence being photographed in 1895 by means of an ingenious method due to Professor Hale, which reached to a distance of 281,000 miles from the Sun's limb. The rapidity with which these prominences appear to rise and change their appearance is not perhaps a conclusive proof that the gases which they contain move with great velocity, for these gases are quite possibly always present, and the prominence may only be a sudden lighting up of the gas, or the rapid transmission of an effect, which does not actually require the transmission of a material body. But the tangential velocities observed at the limb of the Sun within the chromosphere have not at present been explained in a satisfactory way except by assuming that there is an actual motion of hydrogen and of the other gases which form the chromosphere. This tangential motion is far more violent than anything which is required for the convection currents necessary to maintain the temperature of the solar surface. Professor C. A. Young, of Princeton University, states that a velocity of a hundred miles a second is often exceeded, and that twice this velocity is occasionally reached. There can hardly be a doubt as to the facts, but their explanation seems to me more difficult than has been generally recognized. Professor Young says on this point:[1]

> It would seem that thus we might explain how the upper surface of the hydrogen atmosphere is tormented by the uprush from below, and how gaseous masses thrown up from beneath should, in the prominences, present the appearances which have been described. Nor would it be strange if veritable explosions should occur in the quasi pipes or channels through which the vapors rise when, under the varying circumstances of pressure and temperature, the mingled gases reach their point of combination; explosions which should fairly account for such phenomena as those represented in Figs. 69 and 70, where clouds of hydrogen when thrown to an elevation of more than 200,000 miles with a velocity which must have exceeded, at first, 200 miles per second, and very probably taking into account the resistance of the solar atmosphere, may, as Mr. Proctor has shown, have exceeded 500—a velocity sufficient to hurl a dense material entirely clear of the Sun's attraction, and send it out into space, never to return.

My doubt as to the correctness of the above explanation is based on the fact that the highest velocity that a gas can reach when forced to move by differences of pressure is equal to the velocity of sound in the gas, where, of course, the temperature of the gas has to be taken into account in calculating the speed of sound waves. In order that a velocity of 100 miles a second may be possible in monatomic hydrogen, it is necessary that the temperature of the gas should be more than two million degrees, for in no other way can the velocity of sound in hydrogen reach so high a value.[2] On the other hand, if at a temperature of

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[1] *The Sun*, p. 207.

[2] The velocity of sound may for violent disturbances be greater than that calculated by the ordinary formula, but there is reason to believe that the calculated velocity cannot be exceeded many times.

(Note added February 1903.) Since the above was written, Professor Julius, of

10,000 C., at which we may imagine the solar surface to be, a gas can rush out under the action of a pressure, however great, with a speed of 100 miles a second, the mass of its molecules must be over 200 times less than the mass of the hydrogen atom such as we know it. Sir Norman Lockyer has recently expressed the opinion[1] that the true spectrum of hydrogen such as is seen in the prominences is due, not to the hydrogen atom as we know it, but to a much smaller one, derived from it by dissociation, and he has estimated this smaller atom to have a mass about sixty times smaller than the hydrogen atom. If this view were accepted the difficulty would disappear, and the observed high velocities might be explained by internal pressure. But there is a difficulty in believing such small masses to be capable of emitting visible radiations.

Leaving out of account for the present the possibility of such a great subdivision of atoms, there are, to my mind, only three courses open to us. We may, in the first place, deny the necessity of admitting the existence of velocities as great as those I have named. As regards radial motion outward from the Sun, the evidence in favor of the reality of these velocities is not perhaps conclusive.[2] But the tangential velocities at the limb of the

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Utrecht, has made the ingenious suggestion that many of the appearances we observe on the Sun's limb are not real, but are due to an optical illusion, produced by anomalous dispersion. I do not think that, so far, the efforts to account for prominences in this way have been successful, but at present I only wish to point out that the explanation does not get rid of the difficulty which has been pointed out in the text, for the rapid change in appearance, which indicates apparently a large radial velocity, would, according to Professor Julius, still be accounted for by the propagation of some disturbance, though not by a projection of matter. But the velocity of sound is the limiting velocity for the propagation of any disturbance, whether of matter itself or of any arrangement of matter, and, therefore, a large observed velocity is equally fatal to the theory of anomalous dispersion and to the older theory.

[1] *Inorganic Evolution*, p. 182.

[2] (Note added February 1903.) Professor Hale (*Astronomy and Astro-Physics*, 2, 611 and 917) has described a remarkable outburst on the Sun's surface, the vapors produced by the outburst quickly covering a small portion of the Sun's disk, and obscuring two Sun-spots and a number of faculæ.

After the outburst, however, it was found that no permanent change in the appearance of Sun-spots and faculæ had taken place, and Professor Hale concludes from this that the obscuring vapors must therefore have been well above the layer of spots and faculæ. The velocities of those vapors during the outburst must have been very large indeed.

Sun, which are velocities parallel to the solar surface, have been observed to be as great as the radial velocities, and these must be real unless some other cause may produce displacements of spectroscopic lines. One such cause recently discovered, and already mentioned, is pressure, which increases the wave-length. Other effects might be thought of, which may act in the same direction, but it is much more difficult to imagine any cause which can produce a *shortening* of wave-length. As far as I can judge from the published accounts and drawings, a great tangential velocity at the Sun's limb is as often observed to take place *toward* us as *away* from us; hence, even if two causes may act, one shortening and the other lengthening the waves, it does not seem probable that the two causes would act with equal frequency and to an equal extent in both directions. For the present we are forced to admit only known effects, and hence we are forced to recognize the reality of the great velocities which have been deduced from the observations.

Various attempts have been made to account for a number of phenomena which are observed on the solar surface by electrical actions, such attempts being based on the supposition that the Sun as a whole is a highly charged electrified body. But we know that no body at the temperature of the solar surface could permanently retain an electric charge. If there is therefore a permanent electric force, there must also be a permanent electromotive force tending to drive negative electricity from the inside to the outside, or *vice versa*. There is nothing improbable in such a supposition, as the phenomena of atmospheric electricity show. The surface of the Earth is charged with negative electricity, and though we know that every burning fire, and every wave of the sea breaking into spray, tends to dissipate that charge, it yet is permanent, and remains without apparent diminution. We conclude that some cause, upon which meteorologists and physicists are not yet agreed, exists, which tends to bring the dissipated electricity back to the Earth, and we are confirmed in this conclusion by the fact that falling drops of rain are more frequently charged negatively than positively.

We are therefore quite at liberty to admit a high charge of electricity at the surface of the Sun, which probably does not, however, exert any electric force, except near its surface; the outside being screened by opposite electrification. The only way which occurs to me as possibly causing an appreciable electric force at a distance greater than the solar diameter would be to suppose the existence of highly eccentric meteoric swarms, which, passing near the Sun, would carry the neutralizing charge out into space. The streamers of the solar corona might be due to electric discharges between such retreating swarms and the Sun.

If the Sun is a highly charged electrified body, velocities like those observed in the atmosphere are possible, if these velocities are radial, *i. e.*, from the center of the Sun or toward it, but I am unable to satisfy myself that the observed tangential velocities can be explained by electric action. There remains only one way of accounting for these velocities, and that is to conclude that they are either directly due to meteoric matter circulating around the Sun, or indirectly to meteoric matter falling into the Sun, and locally generating a temperature sufficiently high to allow of molecular velocities of 200 miles per second. The velocity of a piece of matter circulating around the Sun and close to its surface in a circular orbit is about 270 miles per second. Such a piece of matter would tend to carry with it the very tenuous gases which are floating above the solar surface, and may well impart to them a velocity ranging from 100 to 200 miles. If actually falling into the Sun, the conversion of their motion into heat, or the kinetic energy supplied by the splash, would be sufficient to account for the observed velocities.[1]

The explanation of the violent disturbances which are observed to take place on the solar surface does not come within the range of my main subject, but it was necessary to point out

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[1] (Note added February 1903.) Matter falling into the Sun and producing what has been called a "splash" could account for velocities very much larger than that of the velocity of sound; in fact, there is no limit to the velocity that could be generated in this fashion, as the energy of impact is, at the first instant, concentrated into a very small amount of matter. If the splash takes place near the Sun's limb, but on the visible portion, great receding tangential velocities may be observed. If the splash takes place behind the Sun's limb, the tangential velocities would be approaching the Earth.

that the convection currents, which are necessary to the temperature distribution which is now generally admitted by astronomers, are actually observed to take place on the surface of the Sun with greater violence than we might *a priori* have expected. A detailed study of solar phenomena is in my opinion the only sure guide in our investigations on stellar constitution, and it is probable that many of the unsolved problems, which still meet us in the interpretation of stellar spectra, will be cleared up in the solar and terrestrial laboratories rather than by mere statistical comparisons and classifications. There are, in fact, many similarities between solar and stellar phenomena. One of the most curious facts revealed by the photographs of star spectra is, as has already been pointed out, the peculiar behavior of calcium, which forms the main connecting link between hydrogen and metallic stars; and this behavior of calcium shows itself with equal persistency in the spectra of solar prominences, which, as regards the hydrogen lines, do not present a spectrum far different from that of *a Aquilæ* or *Procyon;* while the similarity between the spectrum of the chromosphere and that of some of the stars has been pointed out by Sir Norman Lockyer.

Before leaving the subject of the Sun, I may refer briefly to an argument which seems to me to be fatal to any theory which involves the decomposition of the elements right through its mass. We may say with certainty that no amount of pressure can increase the density of any substance much beyond what it is in its liquid state. Liquid hydrogen has a density of about 0.09, or less than the fifteenth part of the average density of the Sun. I conclude that the interior of the Sun cannot be made up of hydrogen or of any substance which might be formed by the breaking up of hydrogen, for such decompositions are, as far as we can judge, never accompanied by an increase of density. On the other hand, the mean density of the Sun is quite consistent with the supposition that its interior is mainly composed of the same substances as are known to us on the Earth.

We may now return to the main subject of our inquiry, which is the critical discussion of the arguments that have convinced the great majority of astronomers of a process of evolution which in the course of time makes each star pass successively through a number of stages, in which the spectrum changes from that of the helium stars to that of the hydrogen stars, and hence to that of stars with prominent calcium lines and of the solar stars.

The first fact which requires explanation is the one which is generally, though not universally admitted, that the temperature of the photosphere of the stars diminishes in the order in which they have just been named. If the hydrogen star is always hotter than the solar star, this would suggest that the chemical composition stands in some direct causal relationship to the temperature, but it is open to discussion which is the cause and which the effect. Is the photosphere of *α Leonis* hotter because it is surrounded by an atmosphere chiefly containing hydrogen, or does *α Leonis* only show us the hydrogen spectrum because its atmosphere is too hot to show anything else? The discussion of this point is altogether independent of our ideas regarding evolution. Even if we do not wish to enter at all into the previous history of a star or its future development, we are bound to search for an explanation of the constitution of the present universe, which shows us hydrogen stars and solar stars, the former being apparently hotter than the latter.

But if we take the theory of evolution into account, we have further to explain the fact that, if the above be true, a star cools as it grows older, while the theory of Homer Lane, of which an outline has been given, states that the star should get hotter. The apparent disagreement between theory and observation has been a stumbling-block to astronomers, but it is due in great measure to the want of definiteness in our meaning, when we speak of the "temperature" of a star. We do not observe the temperature of the center, or the temperature of the gaseous mass below the photosphere, and it is with this temperature that the theoretical analysis deals. What we can observe is the photosphere and the absorbing layer above it, and the temperature of these portions of the Sun are not touched by Lane's theory. If our ideas of the photosphere are correct, and it consists of condensed clouds of metallic or carbon vapor, the temperature of these clouds will be quite independent of the temperature inside the star; and, for all we know, might under certain circumstances remain the same for a long period of a star's life, during which time the star may condense to a fraction of its original volume, and its interior become hotter and hotter, until the condensation has reached the point at which the laws of gaseous compression no longer hold. The surface of a star is pouring out energy in the form of radiation, and the temperature of the surface will depend on the balance of a number of delicately poised conditions. Equilibrium is reached when the loss of heat by radiation is balanced by an equal gain of the heat from the inside or from the outside. The gain in the case of our Sun is in great part due to the convection currents from beneath, which keep the photosphere at the temperature at which, under the existing pressure, the metallic vapors condense. So far we should expect the photosphere to become more luminous as the star contracts, because the greater the intensity of gravitational attraction, the more active the convection currents may be expected to be. But two factors may operate in the opposite direction. In the first place, we must not assume that the inflow of outside meteoric matter, which not so long ago was considered to be the chief cause of the maintenance of solar heat, is altogether inactive. Even in the case of the Sun, it has already been pointed out that several phenomena point directly to the generation of heat at the surface of the Sun by the impact of falling masses. What in the Sun is a subordinate cause may in some of the stars become predominant, and the photosphere may recuperate itself for the loss of energy which it radiates into space, not only from the inside, but also from the outside. If this is the case, we need not be surprised that the temperature of the photosphere is apparently higher in the younger stars, or that the spectrum of these younger stars resembles that of the solar prominences.

But even without having recourse to outside influence, it is possible to account for the higher temperature of the hydrogen stars in a more direct way, by making the hydrogen atmosphere itself responsible for it. The temperature of the photosphere must be largely affected by the absorbing properties of the gases surrounding it. If, for instance, these gases were largely to absorb the infra-red radiation, the effect of such absorption would be observed in a rise of temperature. We need only point, in illustration of this, to the way in which the glass roof and sides of a hothouse protect the plants inside against loss of heat by radiation into space. If it were possible to imagine hydrogen to absorb infra-red rays, this gas would, by stopping the loss of these rays, increase the visible, and especially the blue and violet, radiations, and the fact that the metallic lines shown by hydrogen stars are principally the high temperature lines would thus be accounted for. Such an explanation will only remain a mere surmise, unless it is confirmed by independent evidence, but perhaps the phenomena accompanying the formation of faculæ on the Sun may be found to furnish such evidence, although only of an indirect character. The faculæ are bright streaks on the solar surface specially seen in the neighborhood of spots, and, according to recent observations, they are closely connected with the prominences which seem chiefly to lie above them. If the suggested explanation for the high temperature of hydrogen stars be correct, the same explanation would apply to any portion of the solar surface which has masses of hydrogen hanging over it, and the increased luminosity of those portions of the Sun which lie underneath the prominences, would be a necessary consequence. To prevent misunderstanding, it is well to point out that the infra-red absorption need not be due to the same molecules of hydrogen which give the well-known hydrogen spectrum, and which are almost certainly not identical with the diatomic hydrogen molecule which we prepare in the laboratory. The luminous hydrogen in the stars must be surrounded by cooler hydrogen, and the space surrounding the prominences will similarly contain masses of cool hydrogen, having radiating and absorbing properties differing from those of the luminous substance. If I have dwelt on an explanation which at present is little more than a guess, it is only to emphasize that we need not hesitate on theoretical grounds to accept the evidence of observation, that the photosphere of the hydrogen stars is hotter than the photosphere of a star giving a solar spectrum. The suggestions I have put forward are sufficient to show that the temperature of the photosphere is regulated by considerations which lie altogether outside the calculations of Lane.

We are now prepared to admit that the hydrogen star is hotter than the solar star, and that, if there has been a process of evolution, this hydrogen period of a star is earlier than the solar period. The reason for this second statement will appear more clearly farther on. This brings us to the next stage of our problem. Why does the hydrogen disappear in the process of cooling, and why is its spectrum replaced by that of the metallic vapors? The simplest explanation—simple because it cuts the Gordian knot—is that offered by Sir Norman Lockyer. If the hottest star shows no metallic lines, it is because the temperature is too high for the existence of the molecule which alone can emit the radiation corresponding to these lines. The atoms are decomposed or dissociated, or whatever name we may attach to what must practically be a splitting of what is generally considered an "atom," or, in other words, unsplitable by chemical agencies. When a star cools, and its photosphere has reached the temperature at which the more complex molecule can exist, the corpuscles, according to Lockyer's theory, will recombine and ultimately form metallic vapors such as we know on the Earth. This explanation involves a hypothesis that is possible and consistent, but which, before it can be generally accepted, must either be shown to be the only hypothesis consistent with the facts, or to be supported by strong outside evidence. A great difficulty of the dissociation hypothesis lies in the fact that, as in the case of the Sun, so also in the case of the *Algol* variables, of which the density is approximately known, that density is greater than the density of solid hydrogen, although these stars have spectra which are generally of the hydrogen or calcium type. In order to maintain the theory, it would be necessary to imagine that dissociation only takes place on the surface of the star, and that the pressure inside is sufficient to produce recombination, in spite of the higher temperature which reigns there.

What are the alternative suggestions which have been made? Sir William Huggins, who touched on this in his presidential address delivered to the British Association at Cardiff, draws attention to the effect of convection currents in mixing up different layers of the gaseous matter forming the star. If convection currents could be completely stopped, the heavier gases would sink to lower levels, and the outer layer of a star would be made up of hydrogen and the lighter metallic vapors. It is owing to convection that a mixing takes place, and the stronger the convection the more complete is this mixing. The following quotation will show the position Sir William Huggins takes up in this matter:

> Now, the conditions of the radiating photosphere and those of the gases above it, on which the character of the spectrum of a star depends, will be determined, not alone by temperature, but also by the force of gravity in these regions; this force will be fixed by the star's mass and its stage of condensation, and will become greater as the star continues to condense.
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> In the case of the Sun the force of gravity has already become so great at the surface that the decrease of the density of the gases must be extremely rapid, passing in the space of a few miles from the atmospheric pressure to a density infinitesimally small; consequently the temperature-gradient at the surface, if determined solely by expansion, must be extremely rapid. The gases here, however, are exposed to the fierce radiation of the Sun, and, unless wholly transparent, would take up heat, especially if any solid or liquid particles were present from condensation or convection currents.
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> From these causes, within a very small extent of space at the surface of the Sun, all bodies with which we are acquainted should fall to a condition in which the extremely tenuous gas could no longer give a visible spectrum.
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> Passing backward in the star's life, we should find a gradual weakening of gravity at the surface, a reduction of the temperature-gradient as far as it was determined by expansion, and convection currents of less violence producing less interference with the proportional quantities of gases due to their vapor densities, while the effects of eruptions would be more extensive.
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> At last we might come to a state of things in which, if the star were hot enough, only hydrogen might be sufficiently cool relatively to the radiation behind to produce a strong absorption. The lower vapors would be protected, and might continue to be relatively too hot for their lines to appear very dark upon the continuous spectrum; besides, their lines might be possibly to some extent effaced by the coming in under such conditions in the vapors themselves of a continuous spectrum.

In such a star the light radiated toward the upper part of the atmosphere may have come from portions lower down of the atmosphere itself, or at least from parts not greatly hotter. There may be no such great difference of temperature of the low and less low portions of the star's atmosphere as to make the darkening effect of absorption of the protected metallic vapors to prevail over the illuminating effect of their emission.

In a discussion before the Royal Society in 1897 I took up an essentially similar position.[1] "The chief difference (I then wrote) between a hydrogen and a solar star lies in the more or less effectual mixing up of the constituents. If we could introduce a stirrer into *a Lyræ* there can be no doubt whatever that the low-temperature lines of iron would make their appearance, while, on the other hand, if we could stop all convection currents on the surface of the Sun, the hydrogen which now lies under the photosphere would gradually diffuse out and give greater prominence to its characteristic absorption."

I still believe this statement to be true, but I have modified my opinion in so far as I do not now believe the difference in the condition of the surface of stars like *Sirius* or our Sun to be sufficient to eliminate convection almost entirely in one case and make it the predominant factor in the other. The mean density of *Sirius* is probably not greater than that which our Sun had when its diameter was about five times as great as it is now. But even then, with a gravitational force still greater than that on the surface of the Earth, convection currents must have been active in stirring up and mixing the strata down to a considerable depth below the surface. The conditions which I imagined, in 1897, to hold in the hydrogen stars are not, according to my present opinion, consistent with the formation of a photosphere, which, I now believe, necessarily involves effective convection currents. Hence, there must be some other cause for the elimination of hydrogen out of the atmosphere of stars, when they have reached the solar stage. We are reasoning, of course, on the supposition that the difference in the type of spectra is not due to any inherent chemical difference in the composition of the stars. The evidence for this assumption will have to be further examined, especially in view of the fact that, if my suggestion

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[1] *Proc. R. S.*, 61, 209.

should prove to have a solid foundation, and if the presence of masses of hydrogen is the cause and not the result of the higher temperature of the photosphere, the difficulty we are now trying to overcome disappears. Here, as in the previous discussion, it is not so much my intention to argue in favor of one hypothesis or another, but rather to show the different possibilities which may, in a natural way, account for much that is obscure at present.

If we had only to account for those stars which chiefly show hydrogen and calcium, we might attribute their spectra to the action, in an exaggerated form, of the same cause which produces the prominence spectrum of our Sun. And if we believe that the influx of meteoric matter is directly or indirectly responsible for the prominences, we should be led to suppose that the stars of the *Procyon* type are bodies in which the aggregation of meteoric masses from outside still plays an important part in regulating the temperature and spectrum of the superficial layers. This, though in many ways a satisfactory explanation, does not account for the spectra in which hydrogen is seen without the calcium, nor for other types of spectra which are generally considered to precede the *Procyon* type.

But the disappearance of hydrogen as the star condenses is not perhaps a phenomenon which should surprise us so much. Hydrogen is readily absorbed by many metals, even at a high temperature, and it is highly probable that gases show phenomena of molecular absorption like solids or liquids, when they are subjected to a pressure so high that their density approaches the density of the liquid state. I can see nothing improbable in the supposition that when a star condenses, and its pressure reaches a high value in the interior, it should begin to absorb hydrogen, helium, and possibly oxygen, nitrogen, and the other constituents which have either not been observed in the Sun, or only give faint evidence of their presence. If this opinion is correct, a quantity of matter, suddenly transported from the interior of the Sun to the outside, would violently give up the hydrogen which it was able to contain under its original pressure. The phenomena observed on the surface of the Sun would seem to lend countenance to such a view; at any rate they do not contradict it. Another and perhaps simpler explanation is suggested by considering the process of the formation of a star from its first beginnings. Its consideration may therefore be deferred until we are prepared to look at the question of evolution as a whole. I repeat that it is only my intention to put forward suggestions, which may be found to have some truth in them, and which should, therefore, be taken into consideration.

But from such speculative inquiries we may once more turn to the more solid search for further facts. Results which have an important bearing on our subject have been obtained from the observation of double stars, for they allow us to obtain a value for the state of condensation of the matter composing some of these stars. Professor E. C. Pickering and, later, Mr. Monck have deduced a remarkable equation, which connects together the intrinsic brightness of a star's surface, its mean density, and other quantities which may be obtained by observation. We may thus calculate the density on the supposition that all stars emit an equal amount of light per unit surface. As regards stars showing a similar type of spectrum, this supposition is probably nearly correct, but the results have to be used with caution when comparing a hydrogen and a solar star, for the mere fact that the spectrum of the latter is filled with absorption lines would induce us to believe—quite apart from any question as to the temperature of the surface—that the amount of light leaving the star is less per unit surface for stars giving a solar spectrum, than for stars which only show hydrogen lines. The result of calculation showed that on the average the density of the solar stars was fifteen times greater than the density of the hydrogen stars;[1] but this number was founded on information which, as regards the nature of the spectrum emitted, was, in many cases, deficient. Pending a renewed inquiry into this important subject, I am struck by the slight systematic difference shown between the stars of different spectroscopic types. A density fifteen times as great means, for the same mass, a diameter reduced in the value of 2½ to 1, and even this difference would

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[1] PROCTOR-RANYARD, *Old and New Astronomy*.

disappear if the hydrogen stars had an emissive power six times as great as that of the Sun.

The differences of density shown by individual stars of the same spectral type are considerably greater. Thus γ *Leonis* gives a spectrum almost identical with that of *Arcturus*, which is generally considered to belong to a later period than the solar stage; its density on the assumption of equal emissive powers is 0.0002 as compared with that of the Sun. It is not possible to admit an emissive power 300 times as great as that of the Sun, and hence the density of γ *Leonis* must be very considerably less than that of the Sun. As far as the observations go, the stars which are purely hydrogen stars show smaller variations in density than the solar stars, and have a density which is unmistakably smaller, but great variations are found in the intermediate stages in which the calcium lines are prominent. η *Cassiopeiae*, for instance, has a density almost equal to that of the Sun, being the third in order of density of all known stars, while γ *Virginis*, giving a similar spectrum, has a density sixty times smaller. The difficulty which, in the case of the binaries we have just discussed, arises from our ignorance of the intrinsic brightness of their surface, is overcome in the case of another set of close double stars, the so-called *Algol* variables. These binaries are characterized by the fact that they consist of two stars of unequal brightness, one of which passes periodically in front of the other so as to produce a variation in the combined brightness of the stars. But I must resist the temptation of entering into a detailed description of the peculiarities of these interesting stars, and content myself by referring to the conclusions of A. W. Roberts and H. N. Russell, which have given an average density considerably less than that of the Sun. Thus Roberts finds for the mean of four of these variables 0.18 for the greatest density consistent with the observations, while the corresponding density found by Russell for the average of seventeen variables is 0.20, closely agreeing with the former result. This means a density equal to about one-eighth of the solar density. For the fainter component of *S Velorum*, the greatest possible density is only 0.03 as compared with the Sun. The spectra of these stars all seem to belong to the pre-solar type, and their low density therefore confirms the results arrived at from the consideration of other binaries, though we should not lose sight of the fact that the average density of the stars of the solar type seems to be considerably less than that of the Sun itself, so that the average density of the *Algol* variables is not much less than half the average density of the solar stars.

Interesting facts are brought to light when we investigate the distribution of types of spectra in different parts of the heavens. Such investigations are subject to the dangers accompanying all statistical inquiries, especially when the discussion must, to a great extent, turn on the differentiation between accidental and systematic deviations from the average. We owe a spectroscopic survey of the sky to Professor E. C. Pickering, who, with instruments belonging to the Henry Draper Memorial equipment, classified the spectra of 10,345 stars north of 25° of southern declination, and has since completed the investigation for stars which lie farther south. He has very fully discussed the results of the first of these surveys. Almost exactly half belong to the hydrogen type, 10 per cent. to the intermediate or calcium type, 12 per cent. to the solar type, and 25 per cent. to the *Arcturus* type. If we only take the stars which are brighter than magnitude 6.25, the hydrogen type includes relatively more, viz., 61 per cent., while only 5 per cent. belong to the solar type. The percentage of the Arcturian type is reduced to 18. If the region considered is divided into two equal portions, one lying as much as possible along the Milky Way, and the other away from it, it is found that, of all the stars considered, the Milky Way shows a preference for the stars of the hydrogen type, 3,560 of these stars being mapped in the region of the Milky Way, and 1,658 away from it; the corresponding numbers for the calcium type are 650 and 430. Neither the solar stars nor those having a spectrum similar to that of *Arcturus* show, when their total number is considered, a preference for any particular part of the sky. Out of the total number of stars, 6,252 belonged to the portion of the sky which included, and 4,095 to that portion which did not include, the Milky Way.

When we consider the distribution of stars of different magnitudes, we find that the hydrogen stars, which are of the fourth magnitude and brighter, seem to be distributed pretty evenly all over the heavens, and that it is only the weaker stars which show this effect of clustering in the regions of the Milky Way. The brighter solar stars, on the other hand, seem to be relatively more frequent in the Milky Way than away from it, and the more even distribution shown by the solar and Arcturian stars seems rather due to the fact that the stars of smaller magnitudes belonging to these types are chiefly found in the regions which lie away from the Milky Way. Thus, taking the stars down to the sixth magnitude, we find the numbers in the district of the Milky Way, and away from it, for the hydrogen stars to be 152 and 84, while for the Arcturian stars it is 453 and 341, in both cases an increased number in the Milky Way.

The results obtained by Dr. Frank McClean, who confined himself to stars above the 3.5 magnitude in both hemispheres, are not altogether in accordance with the above. Out of a total number of 276 stars, 30 per cent. only were found to belong to the hydrogen type, 17 per cent. to the *Procyon* or calcium type, while 31 per cent. were Arcturian or solar. An unusually large number, viz., 32 per cent., were classed as helium stars, and this leads to the supposition that a number of stars which figure in Pickering's list as hydrogen stars belong really to the helium subdivision. These helium stars show a very decided tendency to cluster in the Milky Way, but the distribution of the other types is, according to McClean, remarkably uniform. Thus, dividing the sky into two equal portions, the first of which includes the Milky Way, the numbers for the hydrogen type are 20 and 16, a very slight excess in favor of the Milky Way. For the calcium type the numbers are 21 and 27, and for the solar and Arcturian types combined, 45 and 40. The total number of stars of the hydrogen and calcium types is thus remarkably nearly equal to that of the solar and Arcturian types.

A promising line of inquiry has been entered upon by Mr. W. H. S. Monck, who finds that the apparent proper motion of solar and Arcturian stars is considerably greater than that of the Sirian stars. Out of over 5,000 of the latter stars found in the *Draper Catalogue*, 225 are known to have a proper motion of not less than one tenth of a second per annum in one or other of the elements; this gives a percentage of less than 4.5. On the other hand, the percentage of solar and Arcturian stars having the same proper motion is 20 and 15 respectively. This points to the fact that the hydrogen stars are farther away than the solar and Arcturian stars of equal magnitude; or that, on the supposition of an equal distribution in space, and equal average real motion, the hydrogen stars are more luminous, a fact which is quite in agreement with our previous conclusions.

But a novel and unexpected result is the position of the Capellan or solar stars as being the nearest to us, while the Arcturian stars are intermediate between them and the hydrogen stars. Mr. Monck concludes that the Arcturian stars are not cooled-down Capellans, but we shall find that if the explanation I have suggested as to the higher temperature and greater luminosity of the hydrogen stars is correct, the apparently anomalous position of the Arcturian stars is readily explained.

I have intentionally confined myself to a detailed discussion of only two of Secchi's types of stars, but must now briefly refer to other celestial bodies, so that we may be able to obtain a general view of the evidence on which the theory of stellar evolution rests.

There are two kinds of nebulous bodies which may be distinguished by their spectra. One of them, of which the nebula in *Orion* may be taken as a specimen, shows us bright lines of hydrogen, of helium, and of some unknown substance. The second kind, of which the nebula in *Andromeda* is a conspicuous example, apparently give a continuous spectrum, which is weakened so much by spectroscopic dispersion that it is extremely difficult to form a definite judgment as to the nature of the light emitted. While Professor Scheiner believes that he has obtained by photography the absorption lines corresponding to the darkest groups of solar lines, the observations of Sir William and Lady Huggins seem to give very strong evidence of the presence of bright lines in the spectra of these bodies. It is to be hoped that the matter may soon be cleared up, as these nebulæ include all those of spiral form, in which local condensations occur, suggesting a similarity to what we may suppose to be the origin of the formation of more compact celestial bodies. The gaseous nebulæ of the *Orion* kind are nearly all situated close to the Milky Way, while the nebulæ having the *Andromeda* character show the opposite behavior, and obviously avoid the plane of the Galaxy. Passing on to bodies which appear to be intermediate in character between stars and nebulæ, we also find them confined to the Milky Way. These bodies, as seen through a telescope, appear to be stars, but their light, when resolved by the spectroscope, shows bright lines, either alone or in conjunction with dark lines. Their distribution along the Milky Way is irregular, and they tend to cluster together in certain parts of it. These bright line stars vary to some extent in composition; they show as a rule the lines of hydrogen and some unknown lines. Helium appears in some, but not in all of them. There appears to be a gradual transition from these bright line stars to the helium stars, which also are chiefly found in the neighborhood of the Milky Way, and many of which are grouped together; thus all the bright stars of *Orion*, except *Betelgeuze*, and most of the weaker stars are helium stars. The high temperature of these helium stars is testified by the presence of oxygen lines, first identified by Dr. F. McClean, the particular spectrum of oxygen which appears in them being only obtainable in terrestrial oxygen by very intense sparks. The oxygen lines which, for instance, are found in the solar spectrum undoubtedly belong to a more complex molecule, and a lower temperature. There is again, apparently, a continuous transition from the helium stars to the hydrogen, calcium, solar, and Arcturian stars which I have described. The remaining types of spectra belong to lower temperatures still, as in place of the metallic lines, or in addition to them, certain bands appear, which experiments show us invariably belong to lower temperatures than the lines of the same element. Secchi's Type III possesses bands, as to the identity of which there is no consensus of opinion. These stars also cluster in the Milky Way, and a majority of them have the peculiarity of being variable in intensity. The variations are of longer period than that of the *Algol* variables, and at the maximum the bright lines of hydrogen are seen in many cases. Lockyer holds that the carbon bands appear as bright lines, and this view, as far as I am able to judge of the evidence, is probably correct.

Nothing is known as to the reason of the light-variation, but among the causes which can produce the same effect at regularly recurring intervals there is only one which we can at present apply to celestial bodies with any show of reason, and that is the orbital revolution of the bodies around each other; but this question lies beyond the range of our present discussion.

The bands shown by Secchi's fourth type of spectra have been identified, and belong to carbon. The stars showing these spectra are all weak, but over 200 are known. Dunér, to whom we owe the first systematic investigation of these stars, has shown that they also congregate in the Milky Way, not only absolutely, but also relatively to the other stars. Mr. T. E. Espin has further investigated and confirmed this point. Out of a total of 224, the region within ten degrees of the Milky Way includes 123, or more than half, while 74 per cent. lie within twenty degrees of it.

We can only form vague guesses as to the manner in which matter was originally spread through space and has gradually condensed, probably, though not necessarily, through an intermediate nebular stage into the numerous luminous spherical bodies which we observe at night. If an evolutionary process has been going on, which is similar for all stars, there is little doubt that from the bright line stars down to the solar stars, the order has been: (1) helium or *Orion* stars, (2) hydrogen or Sirian stars, (3) calcium or *Procyon* stars, (4) solar or Capellan stars. The Arcturian stars are placed by most observers after the solar stars, but as mentioned above, the researches of Monck seem to bring them to an earlier stage of evolution. Opinions are divided as to the proper place to assign to the stars of the third type. There is, on the one hand, no definite boundary line between them and the Arcturian stars, the transition being gradual; the evidence of an evolution from thé second or solar to the third type is as strong as that which is generally recognized to indicate an evolutionary process from the Sirian to the solar type. On the other hand, the facts that these stars are nearly all variable, that they probably contain bright lines, and that they aggregate in the Milky Way, lend force to Lockyer's contention that the stars are in an early state of formation, and that the low temperature of their absorbing layer indicates that it is still rising in temperature. The carbon stars of the fourth type have been uniformly placed at the end of the succession of spectroscopic changes, though, according to many astronomers, this last stage does not succeed the third type stage, but follows the solar stage. These authorities would either, like Lockyer, remove the third type into the early features of a star's history, or derive it independently from the solar stage. According to this latter view, stars having reached the solar stage would bifurcate, and, according to their chemical composition, develop either the spectrum of the third or that of the fourth type.

The views I have expressed, and suggestions I have made in the previous pages, have led me to the following succession of events, as being in harmony with observed facts.

We may start from matter distributed with approximate uniformity through space, and leave out of account the question whether that original matter was in the form of our present elements, or in some primordial state, out of which our elements have been formed. If the latter case, the conditions must have been such that in different portions of space this primordial matter would condense into our elements, nearly, though probably not absolutely, in the same relative quantities. The formation of the elements I assume to take place simultaneously with the condensation into larger conglomerations.

The first point I want to draw attention to is that the effect of the first condensation must have been accompanied by a rejection of helium, hydrogen, and other light gases, because the development of heat which accompanies the early agglomeration, and raises the temperature of the gaseous bodies, must through the known laws of expansion increase their volume. The gravitation toward the condensed portions of matter not being sufficient to retain the hydrogen, it will diffuse and tend to spread through the adjoining portions of space. In regions where there is no violent motion, it appears to me that matter will tend to concentrate itself around certain nuclei, which will begin to attract each other and clash together. A number of stars will then form, and these stars will at first not contain hydrogen or helium in appreciable quantities. These lighter gases will be left behind as nebulous masses, because it has been shown that unless the gravitation toward the center of a celestial body exceeds a certain value, light gases cannot form a permanent constituent of the atmosphere. This seems to be a not unlikely explanation of the gaseous nebulæ. These bodies are by observation found to be connected with stellar clusters, as has been shown by the remarkable photographs of the nebulous regions surrounding the *Pleiades*, and the spectroscopic investigation of the great nebula of *Orion*.

As soon as a star has grown sufficiently to be capable of retaining the hydrogen and helium, atmospheres of these gases will form around the stars, and the temperature of the photosphere will rise to its maximum. A process of diffusion of hydrogen and helium into the star will at once begin, and may be helped by the process of absorption which has already been alluded to. The helium will be retained first, as it is denser than hydrogen, and we may therefore expect to find helium stars showing the hydrogen lines either weakly or not at all. As a star grows in size the hydrogen will be more and more condensed on its surface from the outside, and we may get a considerable atmosphere of that gas forming around the star. The helium which has first condensed will also first diffuse toward the inside, and we then get the typical hydrogen star. The process of diffusion of the hydrogen, helped quite probably by an absorption due to molecular action, will continue to go on until a stage of equilibrium is reached, in which there is some, but possibly very little, hydrogen near the surface of the star.

It may be objected that the above explanation leaves out of account the peculiar behavior of calcium in the intermediate stage between the hydrogen and solar star. My answer is that the same objection applies to all other explanations. We must at present accept it as a fact that there is a peculiar connection between some of the lines of calcium and the hydrogen line. This is shown by the phenomena which take place on the Sun, as strongly as by those which take place in the stars. The connection may be a chemical one, or may have a hitherto unsuspected origin. I have spoken of these lines which Fraunhofer designated by H and K as "calcium" lines, as so far we have only been able to obtain these lines when there was ground for the supposition that calcium was present. At the same time I do not think many spectroscopists would be surprised if it were found that these lines did not belong to the metal calcium at all. That was the opinion arrived at by Stas for reasons which to my mind are insufficient, but the opinion may ultimately turn out to be correct, even though for the moment experiment does not lend much countenance to it.[1] At present, therefore, we must content ourselves with accepting the peculiar behavior of these lines and their connection with hydrogen as an observed fact, but the acknowledged want of a sufficient explanation of the fact cannot be quoted as an objection to any particular view on the connection between different types of spectra.

A word may also be said as to the peculiarity of helium, which does not show its presence among the Fraunhofer lines, although it is known to be present in the Sun, because its lines appear bright in the chromosphere. There are two causes which may prevent a line from being visible as an absorption line: the vibration which gives rise to the line may be too nearly homogeneous, or it may be too intense.

It has never to my knowledge been pointed out, though it is obviously true, that an absolutely homogeneous vibration can never give rise to an absorption line in instruments of finite resolving powers. That is a possible, though perhaps not a very probable, explanation of our failure to detect helium among the

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[1] (Note added February 1903.) The fact that the difference in the wave-numbers of H and K is nearly double that between the first and second line of the characteristic calcium triplets weighs strongly in favor of the lines being due to calcium. While writing the above I had for the moment forgotten this argument.

absorption lines. The second explanation is contrary to what is generally accepted as true, but only because writers are accustomed to consider the radiation from the solar photosphere to be the radiation of a perfectly black body. If the drops or liquid masses which form the photosphere have any power to reflect or scatter light, such as for instance we know rain drops to possess, the solar radiation need not, as regards intensity, exceed, say, half that due to a black body of the same temperature. It would then become quite possible for a *cooler* body in front either not to show any absorption lines, or even to show them as *bright* lines.[1] The absence among the Fraunhofer lines of the high temperature radiations observed in the chromosphere is probably due to this cause.

Returning now to the secular changes in the stars, I may point out the distinctive features of the views which I have suggested. These views, in the first instance, open out the possibility of much greater variations in their life-history than has generally been admitted. The amount of hydrogen, according to my present view, which a star is able to condense depends on its mass, and on the amount of hydrogen which happens to be present in the neighborhood. Whatever there was originally may already have been drawn toward a previously formed and bigger star. Hence the possibility that a star may form and never pass through the hydrogen stage. Even when the star has as small a density as γ *Leonis* probably has, it may give the spectrum of a solar star, simply from the want of a hydrogen atmosphere. On the other hand, there may be stars which, having attracted a large quantity of hydrogen, but being of comparatively small total mass and small size, are not able to absorb the gas completely, and may remain hydrogen stars without passing through the solar stage at all. Finally, the difference between the Arcturian and solar star may not be one of age at all, but of mass. If the Arcturian star is one which is bigger, it will be able to absorb the hydrogen more completely, and the final

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[1] (Note added February 1903.) I have obtained interesting results by a mathematical discussion of the phenomena of radiation through a foggy atmosphere. These I hope soon to be able to publish in this JOURNAL.

state of equilibrium will be such that the hydrogen lines will be thinner than in the Capellan or solar star.

This seems a plausible explanation of the results of Mr. Monck, who finds the Arcturian star to have a smaller proper motion than the solar stars. They are, if my views are true, brighter though cooler, because their surface is larger, and hence, on the average, they are farther away. The theory, if I may call it so, also gives an explanation of a very curious fact, which I venture to think has not so far been satisfactorily accounted for. In the case of double stars, it is often found that the brighter one is yellow and gives a solar spectrum, while the smaller one is blue and gives a hydrogen spectrum. The larger one, though it may originally have attracted more hydrogen to itself, will be able to absorb it more rapidly, and thus pass through the stages of spectroscopic evolution more quickly.

There is a marked difference between this explanation and that advocated by Sir William Huggins, according to whom a star of small mass would run rapidly through the various stages of evolution. We both agree, of course, in the main fact, that a small mass would lose heat more rapidly, but, according to the views here put forward, there is a counterbalancing tendency in the fact that a large mass would absorb the hydrogen more quickly, and therefore show a more rapid tendency to pass from the state in which it gives a hydrogen spectrum to the state in which the metallic lines become prominent.

I will not discuss the question of the spectra of the third and fourth types, for the reason that we have not sufficient data to form any decided opinion about them. As regards the spectra of the third type, it has already been mentioned that opinions differ as to whether their position is anterior to the hydrogen or posterior to the solar star, and there are valid arguments on both sides. The carbon stars are really disconnected from the others, and though they may ultimately be found to have a place in a general system of classification, there is at present nothing to show that they are not *sui generis* and the result of condensation in a space where carbonaceous matter happened to be abundant. It has already been mentioned that they seem to show bright lines, and therefore probably belong to an early, rather than a late, stage of condensation. I know that the great principle of uniformity will be quoted against any supposition that a particular class of stars is essentially different in its composition from others, but I believe, on the other hand, that the skies bear ample evidence of real differences in composition. There is only need to mention, for instance, the dark bodies which by their passage in front of companion stars, produce the variation of light of the *Algol* variables. The obscuring stars have a density considerably less than that of water, and, as their temperature is low, they must be composed of elements differing widely from those which make up the Earth or the Sun. I cannot therefore admit the validity of an argument based on the so-called law of uniformity, which has always proved a fallacious guide.

Examples are plentiful in the history of science where the law of uniformity might have been quoted, and has been quoted, in support of obsolete moribund theories. Thus the savage, knowing that fire can be made by intelligent hands, unconsciously applied the law of uniformity to conclude that the lightning which set fire to the forests was caused by intelligent beings, surpassing him in grandeur as much as a lightning flash surpassed the feeble fire he could strike himself. When he saw the Sun apparently moving in his orbit, he was compelled by the law of uniformity to conclude that an intelligent being must carry that body in a chariot. When the mediæval magician felt that everything in this world seemed created and centered around man; when, moreover, he saw the Moon obviously describe an orbit around the Earth, he could quote the law of uniformity against the Copernican doctrine, which needlessly removed the center of the universe from what to him seemed its evident position. Even in more recent times false analogies, and conscious or unconscious appeals to the law of uniformity, have been constant sources of deception.

We are led by pure reasoning, and without any consideration of imaginary laws, to consider the universe to be in the state of a clockwork which is running down. We can form some idea guided by our experience and observation, how a star may have formed and may pass through its various stages to extinction; but to say that all stars must necessarily pass through the same stages, to conclude that *Sirius* will ever look like *Arcturus*, is to put ourselves in the position of one, who having discovered that there is a certain law which apparently connects the ages of children with their height, calls the law of uniformity to witness that a man who is five feet high is necessarily younger than one who measures six. If the law of uniformity had reigned at creation, there could have been no life, for there can only be uniformity in death; but if there were sufficient diversity of position, of mixture, and of composition, to allow of aggregations of matter culminating in the formation of worlds, we may be sure that we shall be able to trace that diversity in the present composition of the stellar system. The universe shows law, order, and regularity, but it refuses to be forced from birth to death through a single channel. There is uniformity no doubt, but it is a uniformity which at all times, and in all places, is relieved by endless variety.

A NEW VARIABLE STAR OF UNUSUALLY SHORT PERIOD.[1]

By G. MÜLLER and P. KEMPF.

IN the course of the zone observations for Part III of the Potsdam *Photometric Durchmusterung* it appeared that the two regular measures of the brightness of the star of the seventh magnitude *B.D.* $+56^\circ\!.\,1400$ ($\alpha = 9^h\ 36^m\ 44^s$; $\delta = 56^\circ\ 24'\!.6$ [1900]) in 1899 and 1901 differed from each other by an amount greater than that considered permissible for this *Durchmusterung*. Although the revision observations in the period from April 19 to June 4, 1902, left no doubt as to the variability of the star, they nevertheless gave no indication as to the character of the variation. The measures were continued until the end of July, 1902, and later resumed after the appearance of the star in the eastern heaven, without our succeeding in detecting the character of the variation. It was not until the 13th of January of this year, when the star was several times observed during a period of three hours in the course of the evening, that a decline and rise of the light could be established and the time of minimum approximately derived as about $9^h\ 20^m$ Potsdam M. T. This showed that the light changes occurred in a comparatively short time, and the star was therefore observed on the same night at intervals of ten minutes until shortly before sunrise. A definitive conclusion as to the still somewhat doubtful character of the light-variation was reached through the observations of January 14, which were carried on without interruption from $4^h\ 48^m$ until $9^h\ 19^m$ Potsdam M. T. They furnished a complete view of the whole light-curve, and thus led to the discovery of a variable star with the extraordinarily short period of only four hours, the shortest so far known.

All of our measures of the new variable are summarized in tabular form below. The first six values are taken from the zone

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[1] Translated from advance proofs, furnished by the authors, of a paper to appear in the *Sitzungsberichte der K. Akad. der Wiss. zu Berlin.*

observations for Part III of the *Potsdam Durchmusterung* in which the variable is compared with fundamental stars. Fundamental stars were also used for comparison at the next three observations on June 10 and 25, 1902. But from June 28, 1902, the near-by star *B. D.* + 54°1329 ($\alpha = 9^h\,41^m\,44^s$; $\delta = 54^\circ\,43'.7$ [1900]) served exclusively as the comparison star. For its magnitude we obtain from comparisons with fundamental stars the following ten values: 7.65, 7.73, 7.81, 7.77, 7.68, 7.82, 7.64, 7.63, 7.75, and 7.85, the mean of which is 7.73.

The first five columns of the following table contain successively the date of observation, the local sidereal time, the Greenwich Mean Time, the designation of the observer, and the magnitude of the variable as derived from the measures. The last three columns of the table will be explained later.

Date		Sid. Time	G.M.T.	Obs.	Mag.	C.	O.-C.	Epoch
1899, May	29	$15^h\,16^m$	$9^h\,55^m$	K	7.76	7.94	−18	−7942
1901, January	17	4 50	8 12	M	8.33	8.04	+29	−4358
1902, April	19	14 13	11 32	M	8.12	8.18	− 6	−1617
April	22	14 2	11 9	K	8.58	8.40	+18	−1599
June	2	15 29	9 55	M	7.89	7.90	− 1	−1354
June	4	15 22	9 40	K	7.97	7.90	+ 7	−1342
June	10	15 15	9 10	M	7.84	8.01	−17	−1306
June	25	15 47	8 43	M	8.18	8.29	−11	−1216
		16 3	8 59	K	8.19	8.17	+ 2	
June	28	16 39	9 23	M	7.87	8.05	−18	−1198
June	29	16 42	9 22	K	8.06	8.07	− 1	−1192
July	5	17 17	9 33	M	8.13	8.05	+ 8	−1156
		17 21	9 37	K	8.11	8.03	+ 8	
July	6	16 53	9 5	M	8.28	8.23	+ 5	−1150
		16 58	9 10	M	8.18	8.20	− 2	
July	12	16 38	8 27	K	8.36	8.55	−19	−1115
		16 46	8 35	M	8.29	8.57	−28	−1114
July	15	17 19	8 56	M	8.43	8.40	+ 3	−1096
		17 24	9 1	M	8.27	8.35	− 8	
July	16	17 7	8 40	M	8.44	8.57	−13	−1090
		17 17	8 50	M	8.51	8.48	+ 3	
		17 23	8 56	M	8.60	8.41	+19	
July	19	18 6	9 27	M	8.30	8.19	+11	−1072
		18 11	9 32	M	8.29	8.16	+13	
July	21	16 57	8 10	M	8.14	8.12	+ 2	−1061
		17 2	8 15	M	8.04	8.16	−12	
		17 7	8 20	M	8.21	8.22	− 1	
July	28	17 10	7 56	M	8.07	8.00	+ 7	−1019
		17 15	8 1	M	7.91	8.02	−11	
		17 30	8 16	M	8.09	8.11	− 2	
November	27	3 3	9 47	M	8.11	7.90	+21	− 287

Date	Sid. Time	G.M.T.	Obs.	Mag.	C.	O.-C.	Epoch
1902, December 11	$3^h 11^m$	9^h 0	K	8.18	8.04	+14	− 203
December 12	3 7	8 52	M	8.17	8.08	+ 9	− 197
	3 13	8 58	K	8.09	8.05	+ 4	
December 13	3 36	9 17	M	8.02	7.98	+ 4	− 191
	3 43	9 24	K	8.03	7.95	+ 8	
December 14	3 53	9 30	M	7.81	7.94	−13	− 185
	3 59	9 36	K	7.91	7.92	− 1	
1903, January 12	4 23	8 6	M	8.16	8.26	−10	− 12
	4 31	8 14	K	8.34	8.41	− 7	
January 13	3 26	7 5	M	7.90	7.93	− 3	− 6
	3 29	7 8	K	7.90	7.93	− 3	
	4 20	7 59	K	8.06	8.15	− 9	
	4 25	8 4	M	8.15	8.21	− 6	
	5 18	8 57	K	8.35	8.32	+ 3	− 5
	5 24	9 3	M	8.19	8.27	− 8	
	6 21	10 0	M	8.00	7.96	+ 4	
	6 28	10 7	K	7.99	7.94	+ 5	
	13 0	16 38	M	8.53	8.52	+ 1	− 3
	13 3	16 41	M	8.46	8.49	− 3	
	13 17	16 55	M	(8.63)	8.34	+29	
	13 28	17 6	M	8.34	8.25	+ 9	
	13 35	17 13	M	8.28	8.20	+ 8	
	13 47	17 25	M	8.04	8.13	− 9	
	13 59	17 37	M	8.05	8.06	− 1	
	14 12	17 50	M	8.03	8.00	+ 3	
	14 21	17 59	M	7.99	7.97	+ 2	
	14 33	18 11	M	7.86	7.93	− 7	
	14 44	18 22	M	7.93	7.91	+ 2	
January 14	0 20	3 56	M	8.27	8.12	+15	− 1
	0 30	4 6	K	8.20	8.22	− 2	
	0 35	4 11	K	8.35	8.29	+ 6	
	0 43	4 19	M	8.38	8.45	− 7	
	0 49	4 25	M	8.64	8.55	+ 9	
	0 55	4 31	K	8.57	8.58	− 1	
	1 4	4 40	K	8.55	8.51	+ 4	0
	1 8	4 44	M	8.55	8.47	+ 8	
	1 15	4 51	M	8.38	8.39	− 1	
	1 22	4 58	K	8.30	8.32	− 2	
	1 26	5 2	K	8.33	8.29	+ 4	
	1 35	5 11	M	8.16	8.23	− 7	
	1 40	5 16	M	8.31	8.19	+12	
	1 45	5 21	K	8.22	8.16	+ 6	
	1 51	5 27	K	8.09	8.12	− 3	
	1 57	5 33	M	8.00	8.08	− 8	
	2 3	5 39	M	8.09	8.05	+ 4	
	2 10	5 46	K	8.02	8.02	0	
	2 15	5 51	K	8.15	8.00	+15	
	2 22	5 58	M	7.99	7.98	+ 1	
	2 29	6 5	M	7.98	7.95	+ 3	
	2 36	6 12	K	7.90	7.93	− 3	
	2 44	6 20	K	7.89	7.91	− 2	
	2 51	6 27	M	7.83	7.90	− 7	
	2 59	6 35	M	7.82	7.90	− 8	
	3 6	6 42	K	7.91	7.90	+ 1	
	3 12	6 48	K	7.88	7.90	− 2	

Date	Sid. Time	G.M.T.	Obs.	Mag.	C.	O.-C.	Epoch
1903, January 14	$3^h 22^m$	$6^h 57^m$	M	7.95	7.91	+ 4	
	3 28	7 3	M	8.00	7.92	+ 8	
	3 34	7 9	K	7.94	7.93	+ 1	
	3 43	7 18	K	8.06	7.95	+11	
	3 49	7 24	M	8.04	7.97	+ 7	
	3 55	7 30	M	8.03	7.99	+ 4	
	4 1	7 36	K	8.05	8.02	+ 3	0
	4 7	7 42	K	7.96	8.04	− 8	
	4 14	7 49	M	8.10	8.08	+ 2	
	4 19	7 54	M	8.21	8.11	+10	
	4 23	7 58	K	8.10	8.14	− 4	
	4 38	8 13	M	8.42	8.33	+ 9	
	4 42	8 17	M	8.43	8.41	+ 2	
	4 44	8 19	K	8.45	8.45	0	
	4 52	8 27	K	8.59	8.56	+ 3	
January 17	0 31	3 55	K	8.02	8.09	− 7	17
	0 38	4 2	K	8.16	8.14	+ 2	
	0 44	4 8	M	8.19	8.19	0	
	0 50	4 14	M	8.40	8.28	+12	
	0 54	4 18	K	8.35	8.35	0	
	1 0	4 24	K	8.41	8.48	− 7	
	1 5	4 29	M	8.50	8.55	− 5	
	1 12	4 36	M	8.56	8.58	− 2	18
	1 15	4 39	K	8.66	8.56	+10	
	1 22	4 46	K	(8.74)	8.49	+25	
	1 25	4 49	M	8.37	8.45	− 8	
	1 31	4 55	M	8.37	8.39	− 2	
	1 35	4 59	K	8.36	8.35	+ 1	
	1 41	5 5	K	8.35	8.30	+ 5	
	1 46	5 10	M	8.24	8.26	− 2	
	1 52	5 16	M	8.24	8.22	+ 2	
	1 55	5 19	K	8.05	8.20	−15	
	2 2	5 26	K	8.12	8.15	− 3	
	2 5	5 29	M	8.10	8.13	− 3	
	2 11	5 35	M	7.90	8.10	−20	
	2 15	5 39	K	7.99	8.07	− 8	
	2 20	5 44	K	8.09	8.05	+ 4	
	2 25	5 49	M	8.00	8.03	− 3	
	2 31	5 55	M	8.09	8.00	+ 9	
	2 36	6 0	K	7.97	7.98	− 1	
	2 42	6 6	K	7.94	7.96	− 2	
	2 48	6 12	M	7.91	7.94	− 3	
	2 55	6 19	M	7.88	7.92	− 4	
	3 3	6 27	K	7.89	7.91	− 2	
	3 10	6 34	K	7.90	7.90	0	
	3 17	6 41	M	7.83	7.90	− 7	
	3 23	6 47	M	8.00	7.90	+10	
	3 31	6 55	K	7.87	7.90	− 3	
	3 39	7 3	K	7.96	7.91	+ 5	
	3 45	7 9	M	8.07	7.93	+14	
	3 50	7 14	M	7.95	7.94	+ 1	
	3 56	7 20	K	8.01	7.95	+ 6	
	4 2	7 26	K	7.93	7.96	− 3	
	4 14	7 38	M	8.15	8.01	+14	
	4 19	7 43	M	8.11	8.03	+ 8	

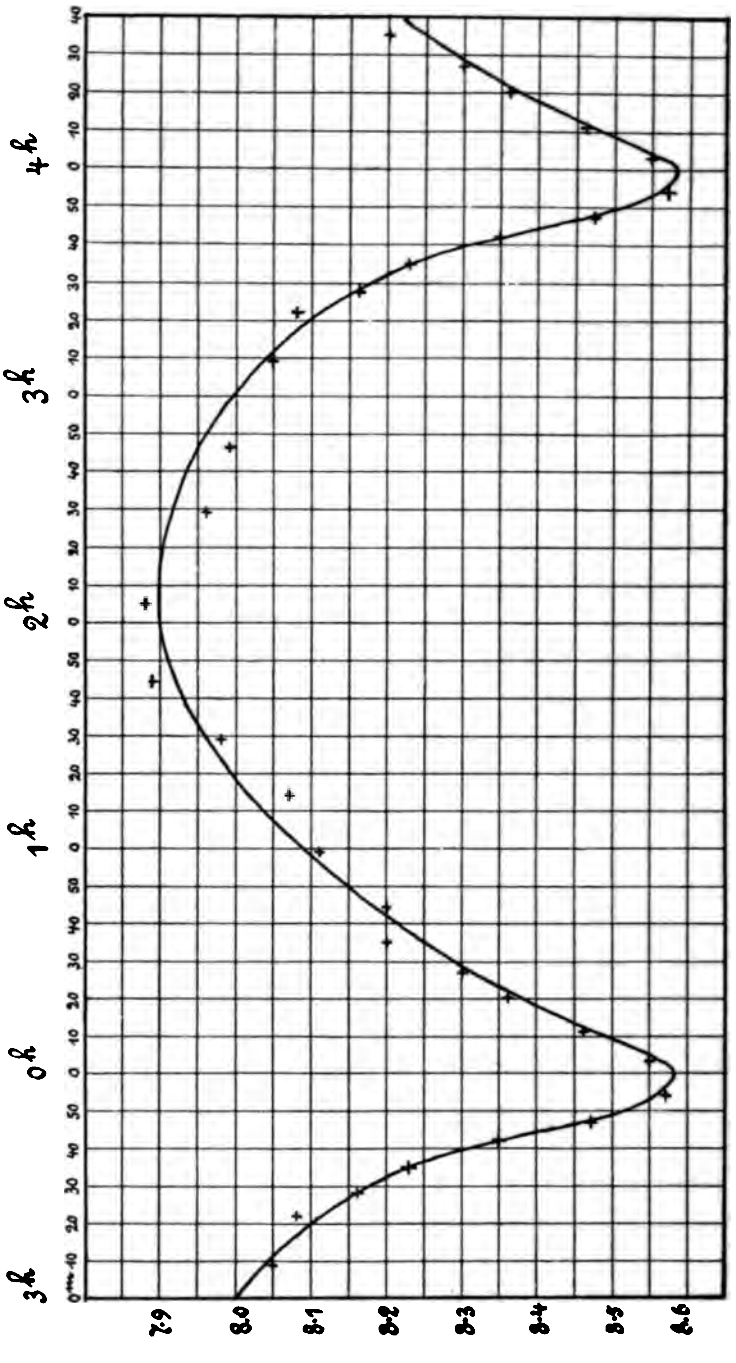
Date		Sid. Time	G.M.T.	Obs.	Mag.	C.	O.-C.	Epoch
1903, January	17	$4^h 26^m$	$7^h 50^m$	K	7.99	8.06	− 7	
		4 32	7 56	K	8.14	8.10	+ 4	
		4 37	8 1	M	8.08	8.13	− 5	
		4 43	8 7	M	8.28	8.18	+10	
		4 46	8 10	K	8.17	8.22	− 5	
		4 52	8 15	K	8.27	8.29	− 2	
		4 55	8 18	M	8.34	8.35	− 1	
		5 0	8 23	M	8.60	8.45	+15	
		5 3	8 26	K	8.58	8.52	+ 6	
		5 9	8 32	K	8.64	8.56	+ 8	
		5 13	8 36	M	8.61	8.58	+ 3	19
		5 18	8 41	M	8.37	8.54	−17	
		5 20	8 43	K	8.54	8.52	+ 2	
		5 26	8 49	K	8.34	8.45	−11	
		5 30	8 53	M	8.33	8.41	− 8	
		5 36	8 59	M	8.28	8.35	− 7	
		5 38	9 1	K	8.24	8.33	− 9	
		5 44	9 7	K	8.19	8.28	− 9	
		5 51	9 14	M	8.15	8.23	− 8	
		5 56	9 19	M	8.17	8.20	− 3	
January	18	4 30	7 50	M	8.01	8.06	− 5	24
		4 36	7 56	M	7.87	8.09	−22	
		4 39	7 59	K	7.99	8.11	−12	
		4 44	8 4	K	8.27	8.15	+12	
		4 48	8 8	M	8.07	8.18	−11	
		4 52	8 12	M	8.31	8.23	+ 8	
		4 55	8 15	K	8.24	8.28	− 4	
		5 1	8 20	K	8.36	8.37	− 1	
		5 4	8 23	M	8.45	8.43	+ 2	
		5 9	8 28	M	8.57	8.53	+ 4	
		5 12	8 31	K	8.45	8.56	−11	
		5 18	8 37	K	8.57	8.58	− 1	25
		5 21	8 40	M	(8.28)	8.56	−28	
		5 26	8 45	M	8.51	8.51	0	
		5 29	8 48	K	8.42	8.48	− 6	
		5 34	8 53	K	8.41	8.42	− 1	
		5 38	8 57	M	8.37	8.38	− 1	
		5 43	9 2	M	8.25	8.33	− 8	
		5 45	9 4	K	8.26	8.31	− 5	
		5 51	9 10	K	8.14	8.27	−13	

The graphical representation of the observations of January 14, 17, and 18 gave the following four minima, the uncertainty of which can be estimated at 10 minutes at most:

Jan. 14 - - - - $4^h 34^m$ G.M.T.
17 - - - 4 40
17 - - - - 8 31
18 - - - 8 34

The combination of these data yielded the first provisional elements of the variable:

Min. = 1903 Jan. $14^d\ 4^h\ 34^m$ G.M.T. + $4^h\ 0^m.0$ E.



LIGHT-CURVE OF *B. D.* + 56°1400.

The uncertainty of the period cannot in any case be assumed to be greater than 1 minute, whence the true value must lie between $3^h\ 59^m$ and $4^h\ 1^m$.

The observations of the year 1902 can be utilized for correcting the first approximation of the period. Since the brightness of the star at minimum is approximately 8.6, it is at once evident that the observations of April 22 and July 16 were made very nearly at the time of a minimum; the uncertainty could hardly amount to more than from 20 to 25 minutes. Combining these two dates together and with the minimum of January 14, it can easily be proved that only the four following periods can come into consideration, each of which can have a play of not more than $\pm$ 0.03 minutes:

$$4^h\ 0^m.65\ ;\ 4^h\ 0^m.21\ ;\ 3^h\ 59^m.77\ ;\ 3^h\ 59^m.33.$$

It may be further shown, with the employment of a light-curve provisionally derived by comparison with the remaining observations of 1902, that the first and the last two of the above four values are to be rejected within their whole range, because they yield inadmissibly large deviations between the computed and observed brightness. The second value only remains, and its application is limited to the range from $0^m.20$ to $0^m.22$. We therefore assume as the second approximation, after a slight displacement of the epoch, the elements:

$$\text{Min.} = 1903\ \text{Jan.}\ 14^d\ 4^h\ 32^m\ \text{G.M.T.} + 4^h\ 0^m.21\ E.$$

This formula was now used for constructing the light-curve of the variable from the measures of January 12–18, the epochs of minima being computed by it, and the differences of time of the separate data of observation as compared with the previous mimimum were formed. In all 143 measures were employed for the light-curve; three of these (distinguished in the table of observations by parentheses) were excluded, as they were clearly affected by somewhat large errors of observations, and would have influenced the result too strongly. The remaining 140 measures were arranged in order of their distance from a minimum and were finally combined in twenty mean values, each from seven measures. These normal values are contained in the following table:

NORMALS.

Distance from Minimum	Observed Magnitude	Curve	O.—C.
$0^{h}\ 3^{m}$	8.55	8.56	−1
0 11	8.46	8.48	−2
0 20	8.36	8.38	−2
0 27	8.30	8.31	−1
0 35	8.20	8.25	−5
0 44	8.20	8.19	+1
0 59	8.11	8.10	+1
1 14	8.07	8.02	+5
1 29	7.98	7.96	+2
1 44	7.89	7.92	−3
2 5	7.88	7.90	−2
2 29	7.96	7.92	+4
2 46	7.99	7.95	+4
3 9	8.05	8.04	+1
3 22	8.08	8.11	−3
3 28	8.16	8.15	+1
3 35	8.23	8.23	0
3 42	8.35	8.35	0
3 47	8.47	8.46	+1
3 54	8.57	8.56	+1

The accompanying light-curve was drawn with the aid of these values. The magnitudes read off from the curve for every five minutes are collected in the following table:

TABLE OF MAGNITUDES.

Distance from Minimum	Magnitude	Distance from Minimum	Magnitude	Distance from Minimum	Magnitude	Distance from Minimum	Magnitude
$0^{h}\ 0^{m}$	8.58	$1^{h}\ 0^{m}$	8.09	$2^{h}\ 0^{m}$	7.90	$3^{h}\ 0^{m}$	8.00
0 5	8.54	1 5	8.06	2 5	7.90	3 5	8.02
0 10	8.49	1 10	8.04	2 10	7.90	3 10	8.04
0 15	8.43	1 15	8.02	2 15	7.90	3 15	8.07
0 20	8.38	1 20	8.00	2 20	7.90	3 20	8.10
0 25	8.33	1 25	7.98	2 25	7.91	3 25	8.13
0 30	8.29	1 30	7.96	2 30	7.92	3 30	8.17
0 35	8.25	1 35	7.94	2 35	7.93	3 35	8.23
0 40	8.22	1 40	7.93	2 40	7.94	3 40	8.31
0 45	8.18	1 45	7.92	2 45	7.95	3 45	8.41
0 50	8.15	1 50	7.91	2 50	7.96	3 50	8.52
0 55	8.12	1 55	7.90	2 55	7.98	3 55	8.56
1 0	8.09	2 0	7.90	3 0	8.00	4 0	8.58

The magnitudes taken from this table are given, along with the observed magnitudes, in the above table of the normal values in the column entitled "Curve." The differences between observation and computation are given in the last column.

As may be seen from the table of magnitudes, and still better from the drawing, the light-variation proceeds very rapidly around the time of minimum, the curve at minimum almost forming an acute angle. The decline to the least brightness is somewhat steeper than the rise thereafter, the two branches not being entirely symmetrical. The maximum is far less sharply pronounced than the minimum, but the observations appear to exclude the possibility that the star remains at its greatest brightness without change for some time; wherefore it cannot be regarded as of the *Algol* type. It is somewhat striking that the normal values at about an hour before the maximum, and similarly some time afterward, lie in general below the curve. The impression is given of a short pause at these times in the increase or decrease of the light, and as if the curve ought to be drawn with two depressions. It cannot be proven without a much greater amount of observed data whether these irregularities are actually real, or are to be assigned to uncertainty or prepossession during the observations. We have paid no attention to them at present.

It should be remarked further that the observations up to this time give no indication of a different brightness at the even and the odd minima. Any irregularity in the intervals between every two successive minima is equally impossible of recognition.

The definitive table of magnitudes was further employed for more closely limiting the second approximation of the period. Here the first two observations of 1899 and 1901 could be employed, the one of which must lie at the time of maximum and the other not far from a minimum. Different trials showed that the most probable value of the period is included between $4^{h}\ 0^{m}.210$ and $4^{h}\ 0^{m}.220$, and in fact the sum of the squares of the residuals was least for the values $0^{m}.212$ and $0^{m}.214$. We adopted the mean from these values, and assume as the most probable elements of the new variable at the present time:

Min. $=$ 1903, January $14^{d}\ 4^{h}\ 32^{m}$ G. M. T. $+\ 4^{h}\ 0^{m}\ 12^{s}.8E$.

The error of the period can hardly be more than $0^{s}.5$, and the correction to it cannot be expected for a number of months. The last columns in the table of measures show how all the observations are represented by the above period. The magnitudes as taken from the light-curve are there given, together with the deviations between observation and computation. The last column contains further the number of the epoch of the minimum preceding the observations in question, reckoned from the initial epoch 1903, January 14. On the whole, the representation may be considered as satisfactory — among the 181 observations there is no deviation greater than $0^{\mathrm{m}}.29$.

The most rapid oscillations in brightness among the variables hitherto known are exhibited by two stars in the star cluster ω *Centauri*, which is rich in variables; their periods are $7^{\mathrm{h}}\ 11^{\mathrm{m}}.4$ and $7^{\mathrm{h}}\ 42^{\mathrm{m}}.8$. *S Antliae* follows next with a period of $7^{\mathrm{h}}\ 46^{\mathrm{m}}.8$. Periods between 8^{h} and 9^{h} are found for several variables in that cluster. *U Pegasi* should be finally mentioned, the period of which is given as $5^{\mathrm{h}}\ 32^{\mathrm{m}}.2$ in Chandler's third catalogue, but which exhibits secondary minima according to Pickering's investigations (*Harvard Circular* No. 23), and has a period of $8^{\mathrm{h}}\ 59^{\mathrm{m}}.7$.

The discovery of the new variable raises the question of the cause of this exceedingly rapid light-variation. We might first think with Zöllner of a rotating body whose surface possesses a very unequal distribution of brightness as a consequence of an advanced stage of cooling. This view is opposed by the white color of the star, for we may assume a yellowish or reddish color for all stars which are strongly cooled off. Another natural supposition would be that of a figure widely departing from a sphere, perhaps a long ellipsoid or a body similar to one of Darwin's figures of equilibrium, which rotate about one of the lesser axes. This explanation, however, would meet with difficulties, because it can hardly be possible to represent the particular form of light-curve observed, especially the very rapid changes of brightness at minimum and the very slow changes around the time of maximum.

We may finally consider the hypothesis that the light-variation is produced by two celestial bodies almost equal in size and luminosity whose surfaces are at a slight distance from each other, and which at times almost centrally occult each other in their revolution. In this case the observed light-curve can be almost exactly represented by computation. The fact that the difference of brightness between maximum and minimum is somewhat less than $\frac{3}{4}$ mag. would indicate that one body is a little smaller than the other, or that the occultation is not quite central. On this hypothesis we have only one difficulty, and the not inconsiderable one, as to whether such a system is mechanically possible and can remain stable for any length of time. But in spectroscopic binaries we have already come to know systems the existence of which formerly had to be considered as doubtful on similar grounds, and it would perhaps be possible by more exhaustive theoretical investigations to demonstrate also the permissibility of the assumption of still closer double stars.

POTSDAM,
February 1903.

THE SPECTROSCOPIC BINARY *o PERSEI*.[1]

By H. C. Vogel.

The Astrophysical Journal for April 1902 (**15**, 214) contains a communication by Mr. W. S. Adams as to certain spectroscopic binaries recently found at the Yerkes Observatory. The following five observations were given of the star *o Persei* ($\alpha = 3^h\ 38^m$; $\delta = 31^\circ\ 58'$):

1902, February 19	+134km
February 21	−77
March 4	+128
April 2	−117
April 3	− 4

A few plates of the spectrum of this star, taken by Dr. Eberhard with Spectrograph IV attached to the photographic refractor (32.5 cm) of the Potsdam Observatory, showed that *o Persei* could also be successfully observed with this telescope with the employment of the large dispersion given by Spectrograph IV. Thus far eighteen spectrograms have been obtained by Dr. Eberhard, with the assistance of Dr. Scholz, and I have undertaken their measurement and discussion.

The star is of the fourth magnitude, and has an ill-defined spectrum of Class I*b*, on earlier plates of which, taken with less dispersion, I was able to measure sixteen lines, chiefly due to hydrogen and helium.[2] Even with low dispersion the lines were very weak and obscure, particularly those of hydrogen. With the higher dispersion of Spectrograph IV there was visible, in the part of spectrum investigated (from λ4315 to λ4495), the hydrogen line $H\gamma$ as a faint brightening in the continuous spectrum. The helium line λ4472, which was also visible and measurable, was very weak and broad; the helium line λ4388, which was measurable on most of the plates, was similar to

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[1] Translated from advance proofs, furnished by the author, of a paper to appear in the *Sitzungsberichte der K. Akad. zu Berlin.*

[2] *Publ. des Astrophys. Obs.*, **12**, 33.

λ 4472. On some of the plates there were indications of the presence of a line somewhat less refrangible than λ4388, and of the *Mg* line at λ4481. This *Mg* line was indeed distinctly visible on several plates when they were viewed with a magnifying glass, but it disappeared under the higher magnification of the microscope. On some plates the helium line λ4388 (and also 4472) appeared fringed with bright edges, similar to the *Mg* line λ4352 and the hydrogen lines in certain stellar spectra. The measurements could therefore be made only upon the very broad, diffuse *H*γ line and upon the two weak and broad lines of the clèveite gas at λ4388 and 4472. On account of the faintness of the *H*γ line in the spectrum of *o Persei*, I could not here employ the method I had previously used with advantage of increasing the accuracy of the measurements of the broad and ill-defined *H*γ line of most spectra of Class I by covering the line with a somewhat narrower pointer, which was then moved back and forth until the diffuse edges of the *H*γ line were equally distant to the right and left of the pointer. For the same reason the double thread could never be used during the measurements.

Dr. Eberhard took the greatest pains to suit the exposure time to the atmospheric conditions, and gave especial care in the development of the plates. The exposures varied from 30 to 60 minutes, averaging ;40 minutes. The slit-width was always 0.02mm.

I should further state that I derived the displacement of the lines in the stellar spectrum from measures of the distance of the three above-mentioned lines from neighboring lines of the *Fe* comparison spectrum. At least six settings were made on each star line, usually with a power of 20; the measurements were also often repeated with the use of different magnifications—from 10 to 35. The precaution was also always taken of not making the settings of the micrometer thread on the star line one after another, but with interruptions, in order that the eye should not be too greatly fatigued by the difficult measments, and in order to be free from any distinct *Auffassung* due to peculiarities of the photographic film. The smallest irregularities in the silver deposit may have a great effect on the weak lines of the spectrum, and it is often difficult to obtain a correct *Auffassung*. To illustrate this further, I would say that with a power of 10 one of the lines on a certain plate appeared to be quite oblique to the direction of the length of the spectrum, while with higher powers, which clearly brought out the grain of the plate, it turned out that the impression of an oblique position of the line was produced by a small cross-mark which had been formed within the stellar line by the running together of several silver grains.

The table on p. 215 gives the velocities resulting from the displacements of the line $H\gamma$ (*a*), λ 4388 (*b*), and λ 4472 (*c*).

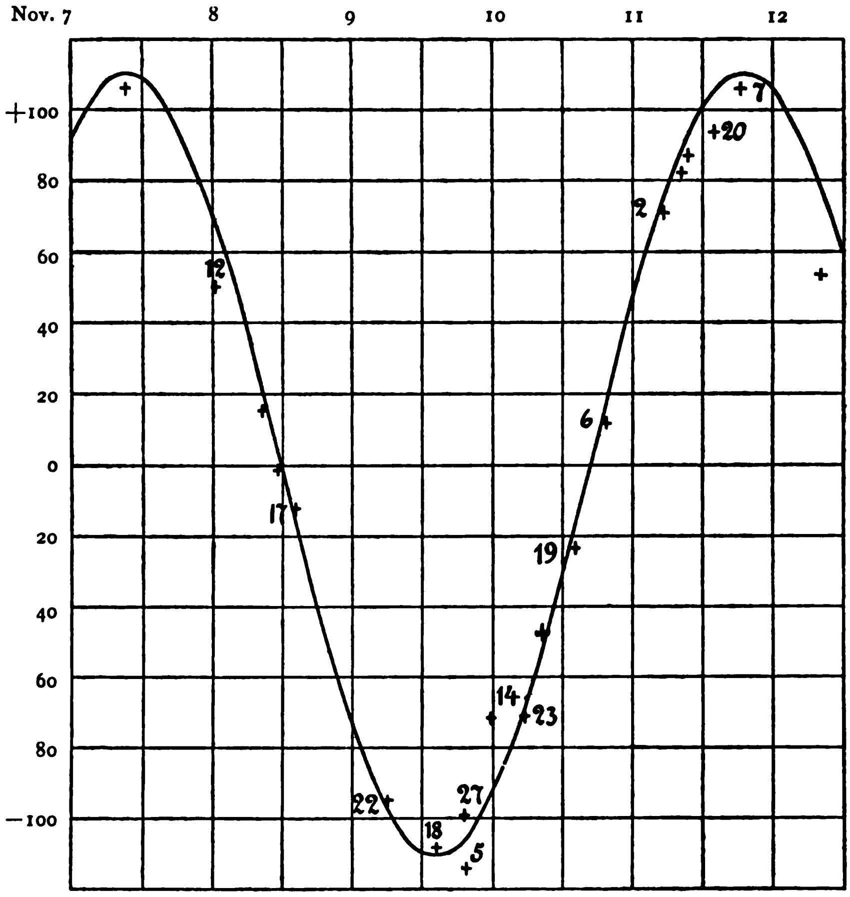
The arrangement of the table requires no further explanation. I have rounded the velocities off to kilometers, in conformity to the low degree of certainty of the measurements. A low relative weight was given to some of the measurements in the record of measures, which has been added in parentheses and was taken into account in forming the means. A: indicates less accuracy. In the last column 1 denotes very good, 4 bad.

On Plate No. 1269 a very fine double line is visible approximately at the position of the *Mg* line λ 4481; it would yield a velocity of −74 km. I regard this fine double line, however, as a defect on the plate, and have therefore not included that measure in the table. Something similar appears within the helium line λ 4472 on Plate 1271, where a fine line is visible somewhat less refrangible than the center of the line; but I must regard this also as a defect in the silver deposit. A velocity of −64 km would be derived from its measurement.

I now sought to combine the observations by a curve, and found that the period may be taken as 4.39 days. Its more accurate derivation will not be possible without further observations extending over a longer time. The assumption of 4.39 days has been sufficient, however, for the reduction of the different observations to the duration of the period, for the purpose of a more obvious graphical representation. It appeared further that there is no noticeable departure from a circular orbit, and the curve in the figure is therefore drawn, not so as to best include the observations, but to represent a circular orbit

Date (Central European Time)	Plate No.	Velocity Relative to Earth	Mean Values of the Velocity		Quality of Observation
			Rel. to Earth	Rel. to Sun	
1902, November $2^{d}.440$	1213	*a* + 51 km *c* + 71	+ 61 km	+ 71 km	2
5.431	1224	*a* −119 *b* −115 *c* −131	−122	−114	2
6.428	1228	*a* + 2 *b* + 12 *c* − 3	+ 4	+ 12	1–2
7.378	1234	*a* + 97 *b* + 87 *c* +113	+ 99	+106	1–2
8.374	1237	*a* + 14 *b* + 21 *c* − 9	+ 9	+ 16	2
8.462	1239	*a* 0 *b* + 17 *c* − 41	− 8	− 1	2
10.361	1242	*a* − 44 *c* − 65	− 55	− 49	2
11.354	1244	*a* + 85 *c* + 61(½)	+ 77	+ 82	3–4
11.401	1245	*a* + 85 *b* + 84 *c* + 77	+ 82	+ 87	1
12.413	1246	*a* + 47	+ 47	+ 52	3
14.355	1252	*a* − 70 *b* − 74 *c* − 80	− 75	− 71	2
17.363	1253	*a* − 28 *b* − 12 *c* − 1	− 14	− 12	1
18.379	1257	*a* −113 *b* −111 *c* −105	−110	−108	1
19.378	1262	*a* − 19 *b* − 24 *c* − 32(⅔)	− 24	− 23	1–2
20.364	1265	*a* + 77 *b* +104 *c* + 98	+ 93	+ 94	2
22.415	1269	*a* − 79 *b* −104: *c* −103	− 95	− 95	2–3
23.408	1271	*a* − 58 *b* − 79(½) *c* − 77	− 70	− 71	1–2
27.351	1282	*a* − 92 *b* −103 *c* − 93	− 96	− 99	1

computed with the above period and a maximum velocity of 110 km. The date of the transition from positive to a negative velocity is taken as November 8.50. There appears to be a



VELOCITY-CURVE OF *o Persei.*

The date is given for those observed points which were reduced to the portion of the curve from November 7 to November 12 with the period of 4.39 days.

slight difference indicated between the greatest positive and the greatest negative values, from which a negative value of several kilometers would follow for the motion of the system.

The accuracy of the observations, though indeed very small, nevertheless turns out better than I had originally expected. On comparing the values for the single lines on a plate with the mean, the probable error of the velocity derived from one line on one plate comes out as ± 9 km; accordingly the probable error of the mean of the measures on one plate will be ± 5 km.

On a closer examination of the velocities derived from three lines on a plate the fact must nevertheless attract attention that, with the exception of those plates on which the lines exhibit a slight displacement, the velocities derived from the displacement of $H\gamma$ are almost always smaller, considered absolutely, than the mean value from the measures of the lines in the spectrum of the clèveite gas.

The derived velocities lie within 20 km on the four plates 1228, 1237, 1239, and 1253.

The velocities derived from the two helium lines are almost equal to that found from the $H\gamma$ line on the three plates 1234, 1245, 1257.

The $H\gamma$ line gives distinctly less values than the other lines on the nine plates, 1213, 1224, 1242, 1252, 1262, 1265, 1269, 1271, and 1282. The deviation averages 13 km.

The first exposure on November 11, No. 1244, may be excluded as too weak, and on Plate 1246 the motion is derived solely from $H\gamma$. The departure of the value from the curve indicates again, however, that it is too small.

If we accept these deviations as real it follows first that after the origin of this difference has been discovered, and it has been taken into consideration, the probable error of the measures would come out still smaller than is given above. But it is of much more importance that the discovery of the occurrence of this anomaly permits a further insight into the binary system under investigation, as I shall show below.

The fact that a periodic doubling of the lines is not perceptible might lead us to assume that one of the bodies of the system is dark, but the marked weakness of the lines of the spectrum of the clèveite gas leads us to conclude, however, that a second spectrum is superposed upon it. The broad and diffuse hydrogen lines, moreover, do not correspond to the typical spectrum of Class I*b* and lead to the further assumption that the superposed spectrum must belong to Class I*a*2.[1] The very delicate metallic lines which appear in this class of spectrum along with the broad and diffuse hydrogen lines, disappear completely as the result of the superposition of this spectrum by the spectrum of Type I*b* of the rapidly revolving body. On these assumptions it is now very easy to explain why the measures on $H\gamma$ yield smaller velocities than those on the cleveite lines. The narrower and less diffuse line of the I*b* spectrum broadens and strengthens the maximum of absorption of the very broad and diffuse $H\gamma$ line of the I*a*2 spectrum when the superposition is absolute. When the two spectra are relatively displaced to each other the line of the I*b* spectrum remains within the broad line of the other spectrum, but the intensity curves of the two lines are so added together that there results a broad maximum, unsymmetrically placed with respect to the center of the combined image of the two lines. The measure of the $H\gamma$ line of the periodically displaced I*b* spectrum is therefore affected by the $H\gamma$ line of the I*a*2 spectrum, and this occurs in such a manner that the measures of the displacement, regarded absolutely, come out too small. The extent to which this occurs naturally depends wholly on the relative intensity of the absorption lines of the two spectra and on the quality of the spectrogram. In spite of the faintness and breadth of these absorption lines it is to be assumed that two maxima could be perceived in the compound $H\gamma$ line at the time of the greatest displacement if both components of the double star are strongly displaced. Even with a less motion of the second star the effect on the *Auffassung* of the compound $H\gamma$ line would have to be stronger than was actually the case. The assumption therefore seems admissible from the observations that the center of gravity of the two bodies must lie very close to the star with the I*a*2 spectrum, or even within it.

After being led to these considerations by the observations I re-examined all the plates of the spectrum of *o Persei* and found

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[1] The width of the hydrogen line $H\gamma$ is about 1.0 rev., that of the helium line 0.3 rev. One revolution of the screw of the measuring machine is 0.25 mm, and the displacement of this amount corresponds to a velocity of 290 km at $H\gamma$, or 340 km at λ 4472.

a very good confirmation of the suspicions above expressed. With a strong positive velocity the brightest point (on the negative) lay unsymmetrically to the center of the $H\gamma$ line, and the line was more diffuse on the side toward the violet, as was clearly seen on Plates 1213, 1234, 1245, 1265. With strong negative motion $H\gamma$ was more diffuse toward the red, distinctly on Plates 1224, 1252, and 1282, and not quite certainly on Plates 1257 and 1271. With the small motion the brightest point (on the negative) in the $H\gamma$ line was exactly symmetrical to the center of the line; the intensity of the absorption was distinctly greater than on plates at other times, particularly on Plates 1228, 1237, 1239, 1253, and 1262; also with a motion of —40 km on Plate 1242, the $H\gamma$ line appeared as on the above-mentioned plates.[1]

Taking 110 km as the greatest velocity, and assuming that the center of gravity of the system lies within the one body, and adopting the period 4.39 days, the distance of the two bodies is computed to be $\frac{6640000 \text{ km}}{\sin i}$, and the mass of the system to be $\frac{0.6 \odot}{\sin^3 i}$, where i is the angle included between the normal to the orbital plane to the system and the line of sight. I have taken for the greatest velocity the value obtained from the curve and also that directly observed. According to the considerations cited above, the mean values from three measured lines might be increased by about 5 per cent., which would increase the maximum values by about 5 or 6 km. If we base our computation upon a maximum velocity of 115 km instead of 110 km we obtain for the distance of the two bodies $\frac{6940000}{\sin i}$, and for the mass of the system $\frac{0.7 \odot}{\sin^3 i}$.

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[1] I ought not to omit to mention that in my previous investigation of the motion of α *Virginis* I was led to similar considerations. *Pub. des Astrophys. Obs.*, 7, 139.

THE MASS OF 85 *PEGASI.*

By George C. Comstock.

This is an interesting binary star ($\alpha = 23^h\ 56^m.8$; $\delta = +26° 33'$), discovered by Burnham in 1878, and soon recognized as possessing an unusually rapid orbital motion. Despite the large difference of magnitudes between its components, 5.7 and 11.3, and their small angular separation — the distance is always less than a second of arc — the star has been well observed, and fairly accordant orbits have been obtained for it by four different computers. The latest of these, by Burnham, assigns to the star a periodic time of revolution of 25.7 years and a semi-axis major of $0''.78$. There is a ninth-magnitude optical companion to the binary whose relative position was first measured by Otto Struve in 1851 and which has been well observed since that time, with the exception of one serious gap between 1852 and 1865, as shown in the following table.

I have recently discussed the comparisons of this star with 85 *Pegasi* to determine the relative proper motion of the stars and have been thus led to consider the possible motion of the bright component of 85 *Pegasi* with reference to the center of gravity of its system. The data of the problem are the observed position angles and distances, θ and ρ, of the ninth magnitude star, C, referred to the bright star, that I shall call A, and similar data, p and s, for the faint companion, B, of the binary system. These latter co-ordinates I have derived from Burnham's apparent orbit[1] for the dates of the available observations of C. I desire here to emphasize the great interest and value of these apparent orbits and to express the wish that a cut showing the apparent orbit might always be published in connection with orbit determinations of binary stars.

For the discussion of the observation we may put

μ = the difference of declination, at an assumed epoch, between C and the center of gravity of A and B.

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[1] *Publications of the Yerkes Observatory*, 1, 270.

ν = the relative proper motion of C and the center of gravity above defined.

τ = the time interval between the given observation and the epoch 1885.54.

k = the fractional part of the distance A — B included between the center of gravity and the star A.

Transforming polar to rectangular co-ordinates, we find for the co-ordinate parallel to the hour circle,

$$\mu + \tau\nu + s\cos p \cdot k = \rho\cos\theta,$$

with a similar equation for the co-ordinate perpendicular to the hour circle,

$$\mu' + \tau\nu' + s\sin p \cdot k = \rho\sin\theta.$$

For the determination of the five unknowns in these equations I have employed the following observations, in which the posi-

OBSERVED CO-ORDINATES, A, C.

Date	Nights	θ	ρ	W	Observer
1851.96	1	114°3′	33.03	0.5	OΣ
52.67	1	113 51	32.60	0.5	OΣ
65.91	1	92 9	18.89	0.5	OΣ
68.77	1	82 24	17.03	0.5	OΣ
70.00	44	77 1	16.06	2	Brünnow
74.66	1	54 24	13.92	0.5	OΣ
76.77	1	40 18	14.02	0.5	OΣ
78.54	4	33 36	14.40	1	β
78.74	1	32 48	14.76	0.5	Dembowski
79.27	8	30 24	14.96	1	β
80.57	4	25 0	15.41	1	β
81.54	4	20 48	16.29	1	β
81.88	1	19 48	16.54	0.5	Bigourdan
82.62	1	15 12	16.98	0.5	OΣ
82.77	3	17 6	17.34	1	β
83.54	1	11 18	17.34	0.5	Seagrave
86.24	3	7 36	19.84	1	HΣ
86.99	3	6 6	21.15	1	Englemann
88.67	5	0 54	21.71	1	β
89.50	4	358 42	22.66	1	β
89.82	2	358 24	22.70	1	Leavenworth
90.52	3	356 42	23.59	1	β
91.56	3	354 42	24.58	1	β
91.94	8	354 18	25.02	1	β
95.06	1	350 0	28.86	0.5	Lewis
95.69	3	348 42	29.27	1	Aitkin
96.75	2	347 48	30.48	1	Aitkin
97.56	2	346 6	31.49	1	Aitkin
97.82	2	345 42	31.74	1	β
98.49	3	344 24	32.53	1	β
98.69	2	344 27	32.90	1	Aitkin
1902.73	3	341 19	37.64	1	Comstock

tion angles, θ, are reduced to the equinox of 1850.0. Since the present discussion is a part of a larger investigation of the proper motions of faint stars, I have assigned to the several observations weights, W, in accordance with a uniform system adopted for that work. While these weights could probably be modified with some advantage, in the present case I do not think that any substantial change would be found in the resulting values of the unknowns.

Numerical equations of the type given above are so readily formed from these data that I refrain from publishing them and pass immediately to the following groups of elimination equations that result from their least square solution.

$$\begin{array}{rr}
\text{In Declination} & \text{In Right Ascension} \\
\mu - 0.0018\nu - 0.3215k = +18''.879 & \mu' - 0.0018\nu' - 0.1175k = +2''.602 \\
\nu - 0.0974k = +\ 9.729 & \nu' + 0.0706k = -8.307 \\
k = +\ 0.631 & k = +0.604
\end{array}$$

The time unit here employed is a decade, but the resulting values of ν and ν' printed below are expressed as annual variations.

The close agreement in the values of k furnished by these two groups of equations inspires some confidence as to its being a real quantity, and in confirmation of this view we may note that physically the value of k must fall between 0 and $+1$, as in fact it does result from the solutions, while a mere computation result is subject to no such restrictions and might have any value whatever.

I adopt as the definitive result of the investigation $k = +0.62$ and with this value find for the epoch 1885.54:

$$\begin{array}{ll}
\mu = +\ 19''.10 & \mu' = +\ 2''.66 \\
\nu = +\ 0.9789 & \nu' = -\ 0.8350
\end{array}$$

I have also derived values of these quantities corresponding to the supposition $k = 0$, and have formed the sums of the weighted squares of the residuals and the probable error of an equation of unit weight, corresponding to these two hypotheses, viz.:

$$\begin{array}{lll}
\text{For } k = 0 & [pvv] = 5''.44 & r_1 = \pm 0''.20 \\
k = 0.62 & [pvv] = 3.04 & r_1 = \pm 0.15
\end{array}$$

These results show a substantial improvement, due to the introduction of an orbital motion for the star A, and corresponding to the adopted value of *k* I find for the ratio of the masses of the components of 85 *Pegasi*,

$$A : B = 3 : 5.$$

For the transition from these ratios to the absolute masses of the stars there are available three determinations of the parallax of 85 *Pegasi*, viz.:

Brünnow -	$\pi = +0''.05 \pm 0''.020$	Filar micrometer,
Flint - - -	$= +0.02 \pm 0.038$	Meridian transits,
Flint - -	$= +0.04 \pm 0.038$	Meridian transits,

and adopting $+0''.04$ as the mean of these values I obtain for the respective components, in terms of the Sun's mass taken as unity,

$$A = 4.3 \qquad B = 7.0,$$

but the adopted parallax is so small as to render these results decidedly uncertain.

The relative masses, however, seem to stand upon an altogether different footing as respects the accuracy with which they are determined, and in the light of current theories of stellar development they present a somewhat remarkable result: A star, A, whose spectrum is of the second type (E, in the *Draper Catalogue*) emits more than 100 times the light of its companion, B, although B is presumably of equal age with A and possesses 60 per cent. more mass than the latter star.

WASHBURN OBSERVATORY, MADISON, WIS.,
January 23, 1903.

THE NEW GASES NEON, ARGON, KRYPTON, AND XENON IN THE CHROMOSPHERE.

By S. A. MITCHELL.

FROM a historical point of view, D_3 is one of the most important lines in the spectrum. When examining in April 1895 the spectrum of a specimen of clèveite, Ramsay announced the discovery of a substance that gave the characteristic helium line, it was felt that a great triumph had taken place for the methods of the "new astronomy." About the same time Rayleigh and Ramsay discovered another new element, argon, and in the early summer of 1898 Ramsay found two more elements, krypton and neon, and subsequently a heavier gas to which the name xenon was applied. Making use of the extremely low temperatures of liquid air and liquid hydrogen, it was found that these five new gases were present in atmospheric air. Investigations of the properties of these gases[1] seem to indicate that the atomic weights are: helium, 4; neon, 20; argon, 40; krypton, 82; xenon, 128; and that they form a series in the periodic table between that of fluorine and that of sodium.

The lines of helium are such prominent ones in the chromospheric spectrum that it would be interesting to see if the other new gases are also present in the chromosphere, and accordingly comparisons have been made between the spectra of the "flash" and of the new elements whose wave-lengths have lately been published.

The flash spectrum was photographed by the writer at the Sumatra eclipse,[2] with an apparatus consisting of a Rowland plane grating of 15,000 lines per inch, having a ruled surface of 3½ × 5 inches, and a quartz lens, the whole mounted so as to give a normal spectrum. The photographs—like most of those at this eclipse—were made through clouds. These poor

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[1] RAMSAY and TRAVERS, *Proc. R. S.*, 67, 329, 1900.

[2] ASTROPHYSICAL JOURNAL, 15, 97, 1902.

weather conditions, however, did not interfere with the spectrum as much as was expected, which is shown by the fact that 374 lines were measured between F and H. The dispersion employed was about one-fifth that of the largest Rowland concave gratings of 21½ feet radius, and 20,000 lines per inch, and about equal to the dispersion of the Lick and Yerkes spectrographs.

Comparisons of the *intensities* of the lines, and of the *numbers* of the lines due to the different elements in the flash and in the solar spectrum, as given by Rowland, led to the division of the elements into three groups (*loc. cit.*, Table V): those giving (1) lines strong in the flash and strong in the solar spectrum; (2) lines strong in the flash, weak in the solar spectrum; and (3) lines weak in the flash, but strong in the solar spectrum.

To the second group belong *H*, *He*, *Sc*, *Ti*, *V*, *Cr*, *Mn*, *Sr*, *Y*, and *Zr*. It has been shown[1] that helium, in consequence of its small density, ascends to great heights above the Sun's surface, and as its layer is covered up gradually by the Moon at the time of an eclipse, the resulting exposure is many times that given to denser but shallower layers, and consequently helium lines in the flash spectrum are very prominent. Taking into account the increasing atomic weights of the series of new gases, and also the behavior of the light and heavy vapors in the Sun's atmosphere, as found out by investigations of the flash, we should expect, as in the case of helium, none of these gases to be found in the ordinary solar spectrum. We should also expect lines of the more volatile gases of the Earth's atmosphere, neon and argon, of atomic weights 20 and 40 respectively, to be present in the flash, while those of the less volatile gases, krypton and xenon, of atomic weights 82 and 128 respectively, are most probably not to be found there.

No lines of these gases appear in the ordinary solar spectrum, but if we make a detailed comparison of their spectra with that of the flash, there seem to be certain lines of the latter that are undoubtedly due to these new gases of the atmosphere.

The most volatile of these were obtained[2] from their solution in liquid air by fractional distillation at low pressure, in

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[1] *Ibid.*, p. 117.

[2] RAMSAY and TRAVERS, *Proc. R. S.*, 67, 329, 1900.

this way removing the greater portion of the helium and neon from this mixture of gases, leaving the argon behind. Many attempts were made to separate the helium from the neon, which were not successful until these gases were subjected to the temperature of liquid hydrogen, when neon was liquified and perhaps solidified, while the helium remained gaseous.

The more volatile gases of atmospheric air uncondensed at this temperature have been examined spectroscopically by Liveing and Dewar, and wave-lengths have been published.[1] In this spectrum appear lines due to neon, to helium, and to free hydrogen in the Earth's atmosphere. These wave-lengths, given, however, only to the nearest Ångström unit, have been compared with those of the lines of the flash spectrum.[2] Although it is difficult to identify with certainty when wave-lengths have no greater accuracy than this, it seems highly probable that nearly all the stronger lines of the most volatile of the new gases are found in the flash, some of them agreeing with lines already identified as corresponding to Fraunhofer lines (in this case it being impossible to separate the lines), other lines identified with lines that have no counterpart in the ordinary solar spectrum. None of the lines of the flash due to these more volatile gases are strong lines like those of helium, their intensities being 0 on a scale where 0 denotes a line seen with certainty and 10 is the intensity of the strongest line. Lines in the flash which seem to belong to these gases and to no others are those at λλ4047, 4398, 4422, 4431, 4540, and 4844.

Several tables of wave-lengths of argon have been published. Kayser employed a large concave grating and published[3] his results to thousandths of a tenth-meter. Most of the strong lines of argon are found in the flash spectrum—but again as weak lines only. Argon lines appear at λλ4180.3, 4200.8, 4259.5, 4266.8, and 4430.3.

The most accurate wave-lengths of krypton are those of Runge, measured with a concave grating and given[4] to thousandths of a tenth-meter. The strongest lines are in a part of

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[1] *Ibid.*, p. 467.

[2] ASTROPHYSICAL JOURNAL, 15, 103, 1902.

[3] *Ibid.*, 4, 1, 1896.

[4] *Ibid.*, 10, 73, 1899.

the spectrum not covered by the flash photographs, and there seem to be no krypton lines in the flash.

The only wave-lengths of xenon are those of Liveing and Dewar,[1] given only to the nearest tenth-meter. Some of the strongest of the xenon lines do not appear in the flash, while the wave-lengths of some less strong seem to agree with those of flash lines; but as the wave-lengths are not accurate enough, it is impossible to say more than that the presence of xenon in the Sun's atmosphere is doubtful.

Consequently, it seems that the more volatile gases of atmospheric air uncondensed at the temperature of liquid hydrogen, together with hydrogen, helium, neon, and argon, are present in the chromosphere, while the evidence in regard to krypton and xenon is inconclusive.

The finding of these gases in the Sun and the undoubted presence of free hydrogen in the Earth's atmosphere have an importance for cosmical physics that can hardly be overestimated. According to Liveing and Dewar, "if the Earth cannot retain hydrogen nor originate it, then there must be a continued accession of hydrogen to the atmosphere (from interstellar space), and we can hardly resist the conclusion that a similar transfer of other gases must also take place,"[2] as has been shown by these distinguished physicists, and again by Dewar in his presidential address before the British Association for the Advancement of Science, these new gases, and particularly the more volatile gases of atmospheric air, play an important part in the spectra of the aurora, of nebulæ, and of the corona. Of more than a hundred auroral rays observed by Stassano, more than two-thirds appear to belong to the more volatile gases of atmospheric air, while the majority of the remainder seem to belong to argon, krypton, and xenon. We are also told by Dewar that of a "list of 339 lines photographed by Humphreys, during totality" (this, however, was called the spectrum of the corona, whereas it was the spectrum of the chromosphere), "only 55 do not differ by more than one unit on Ångström's scale from lines measured in the most volatile gases of the atmosphere, or in

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[1] *Proc. R. S.*, **68**, 389, 1901.

[2] *Ibid.*, **67**, 468, 1900.

krypton or xenon." It seems rather to the present writer that the great majority of these lines more closely correspond to Fraunhofer lines than to the lines of these rare gases.

These gases may take their origin from the Earth itself; in fact, helium and neon are occluded from the waters of the Bath spring in England. The presence of free hydrogen in the atmosphere cannot be explained in this way. It is more likely that hydrogen comes to us in small ionized particles from the Sun, being sent hither, as has been shown by Arrhenius,[1] by the pressure of light, and likewise helium and the more volatile gases are present in the atmosphere through being repulsed from the Sun by the ionization of small particles of these gases.

It seems therefore that the finding of these new gases in the Sun's chromosphere is an independent verification of the truth of the theory of Arrhenius, which states that particles of matter are being continually scattered throughout the universe, starting from one sun and reaching another, with the result that all bodies of the universe are gradually becoming more and more alike.

COLUMBIA UNIVERSITY,
New York City, February 1903.

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[1] *Physikalische Zeitschrift*, November 1900; see also Cox, *Popular Science Monthly*, January 1902.

ON THE OCCURRENCE OF SPARK LINES IN ARC SPECTRA.[1]

By J. HARTMANN and G. EBERHARD.

IN November of last year Dr. H. Konen published in the *Annalen der Physik* (9, 742 ff., 1902), some very valuable researches which he had made on the spectra of electrical discharges in water. This induces us to communicate briefly in what follows the results of investigations in the same field which we carried out last autumn.

In the first place it should be remarked that our observations confirm those of Konen even to details. We have, however, observed some additional phenomena not described by Konen, which seem to be of importance in the interpretation of the processes of electrical luminosity.

Our experiments at first were confined to a thorough study of the spectra of magnesium and silicon, which are of special importance in astrophysics. While we were varying as much as possible the conditions under which these elements were made luminous, we made use, among other things, of the electric arc under water. Here we noticed with surprise that in the spectrum of the arc there appeared lines which had hitherto been regarded as peculiarly characteristic of the spark spectrum.

Konen also has shown for a number of metals that lines in the spectrum of the metallic arc under water are not superposed on a strong continuous spectrum like the spark spectrum produced under the same conditions, but appear only as bright and generally sharp lines; the appearance in the arc under water of lines characteristic of the spark spectrum, however, has not to our knowledge been known hitherto.

When the arc is passed under water between two electrodes of metallic silicon, the spark lines λ 4128, and λ 4131 appear with almost the same intensity as does the chief arc line λ 3905. Under the same experimental conditions magnesium shows the

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[1] Translated from advance proofs, furnished by the authors, of a paper to appear in the *Sitzungsberichte der K. Akad. zu Berlin.*

line at λ 4481, hitherto regarded as characteristic of the spark spectrum, and indeed it makes almost the strongest line in the whole spectrum; at any rate, its intensity considerably exceeds the arc line of magnesium at λ 4352. Both elements further exhibit the noteworthy phenomenon that the lines mentioned, which are known only as very broad and weak lines in the spark discharge in air, are considerably narrower and become more sharply defined, despite their intensity, when produced by the arc under water.

In order to ascertain whether the phenomenon described above was general, the experiments were also extended to other metals, and we were able to produce results entirely analogous with zinc and cadmium. With zinc the very diffused spark lines λ 4911 and λ 4924, when produced by the arc under water appeared strong and relatively sharp. The lines λ 5339 and λ 5379, which Kayser and Runge failed to find in the arc spectrum of cadmium, together with λ 4416, have also been easily obtained by us with the arc under water. We found the aluminium lines λ 4513 and λ 4530 less strong.

Carbon alone remained essentially anomalous, giving, with the arc under water, as Konen also found, no lines, but a band spectrum only.

We now suspected, in connection with a remark by Schenck[1] that the temperature of the electrodes and metallic vapors, no doubt much reduced by the water, might have an influence on the nature of the spectrum, and we thereupon greatly cooled zinc electrodes with liquid air, without obtaining, however, any material change in the arc spectrum. We then allowed sparks from an iron electrode to pass over to zinc placed in a crucible. While the zinc was heating to the melting-point and beyond, several observers (Vogel, Müller, Kempf, Hartmann, Eberhard) estimated the relative intensity of the pair of lines at λ 4911 and λ 4924 as compared with the three lines at λ 4680, 4722, 4809, and it appeared in every case that the intensity of these three lines was greatly augmented in comparison with the pair at λ 4911 and λ 4924 as soon as the zinc was heated.

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[1] ASTROPHYSICAL JOURNAL 14, 131.

In the success of this experiment we might see a confirmation of the above-mentioned conjecture that with ascending temperature of the electrodes the spectrum of the spark approached that of the arc. But it is not improbable that the observed phenomenon occurred merely through the increase of the metallic vapor due to heating the zinc, whereby, on account of the increase of these vapors, the resistance in the path of the spark became less and the spark lines accordingly gave place to the arc lines.

Since an answer to the question entirely free from objection cannot therefore be obtained by these means, we have endeavored to find an explanation in another direction. From former researches (Crew, Basquin) it is known that an atmosphere of hydrogen influences the arc spectrum of magnesium in such a manner that the spark line $\lambda 4481$ stands out prominently. Accordingly we have photographed the arc spectra of a series of metals in a current of hydrogen. It now appeared that spectra obtained in this manner are in fact almost identical with the arc spectra under water, and we are therefore of the opinion that hydrogen, released by electrolysis around the electrodes in water, causes the transformation of the arc spectrum into the form observed by us.

It should be observed that all lines mentioned by us in the foregoing are diffuse and hazy in the spark spectrum, and that it is also just these lines which can be made to disappear in the spark spectrum by the introduction of suitable self-induction, as we have convinced ourselves by our own experiments.

It follows from our investigations that it is not permissible to set apart individual lines of the spectra of metals as characteristic of the spark or of the arc respectively, and from their appearance to draw conclusions regarding the temperature of the corresponding processes of luminosity. The latter point applies particularly in the interpretation of stellar spectra, for which some have sought to make positive statements as to the temperature of stellar atmospheres, based upon the behavior of individual magnesium and silicon lines.

POTSDAM.
February 1903.

THE POSITION OF RADIUM IN THE PERIODIC SERIES ACCORDING TO ITS SPECTRUM.

By C. RUNGE and J. PRECHT.

THE spark spectrum of radium can be admirably observed with the radium bromide recently produced by Mr. Giesel. A few milligrams, which Mr. Giesel was kind enough to place at our disposal for this purpose, was sufficient with a low dispersion for obtaining the spectrum in a much more complete manner than has hitherto been observed, and with greater disperson the readily photographable lines could be investigated as to their behavior in a magnetic field. We thus found that the strongest radium lines are precisely analogous to the strongest lines of barium and the corresponding lines of the related elements *Mg*, *Ca*, and *Sr*. As has been shown by Runge and Paschen,[1] these lines can be grouped as three pairs, which, on account of certain analogies with the spectra of the alkalies, may be designated as the pair of the principal series, the pair of the first subordinate, and the pair of the second subordinate series. In the case of the pair of the first subordinate series there appears along with the line of the greater wave-lengths a fainter line on the side of longer wave-lengths, which Runge and Paschen designate as a satellite. The two lines of each of these three pairs have the same distance for each element, reckoned on the scale of vibration numbers, except that for the pair of the first subordinate series the satellite must be taken instead of one of the lines. But from element to element the distance is, on the contrary, different, increasing in a very regular way with increasing atomic weight, as will be discussed more particularly below. In the magnetic field these lines are resolved into components in a different way, as Runge and Paschen have shown, but so that, reckoned on the scale of vibration numbers, the separation of each line of one element is exactly the same as the separation of the *corresponding* line of each of the other elements.

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[1] ASTROPHYSICAL JOURNAL, 16, 123, 1902.

We have now found that precisely the same thing holds good for radium, so that *Ra* is to be placed with *Mg*, *Ca*, *Sr*, and *Ba* in a group of chemically related elements, as is also demanded by the chemical behavior of radium, in so far as this is known.

The corresponding lines are collected together in the following table:

	Mg	*Ca*	*Sr*	*Ba*	*Ra*
Principal series..............	2803	3969	4216	4934	4682
	2796	3934	4078	4554	3815
First subordinate series	....	3181	3475	4166	4436
	2798	3179	3465	4131	4341
	2791	3159	3381	3892	3650
Second subordinate series	2937	3737	4306	4900	5814
	2929	3706	4162	4525	4533

The separation of the radium line in the magnetic field is very well observable in case of the strongest lines; as yet we have been unable to resolve only the satellite and the line in the green at λ 5814.

As remarked above, the distances between the two lines of the pairs are the same for every element on the scale of vibration numbers. This is also true for radium, as is shown in the following table:

	λ	$\frac{10^8}{\lambda}$	Distance
Principal series...............	4682.35	21356.8	4858.3
	3814.59	26215.1	
First subordinate series........	4436.45	22540.5	4858.5
	3649.77	27399.0	
Second subordinate series......	5813.9	17200.2	4858.6
	4533.33	22058.8	

The deviations of the three distances from each other are sufficiently explained by the errors of observation. They correspond to very small errors in determinations of wave-length.

For *Mg*, *Ca*, *Sr*, and *Ba* the distances increase with the atomic weight from element to element:

	Atomic Weight	Distance
Mg..........	24.36	91.7
Ca..........	40.1	223
Sr...........	87.6	801
Ba..........	137.4	1691

It is natural to regard the atomic weight as a function of the distance and to extrapolate this function for radium. It has already been pointed out by Rydberg and by Kayser and Runge in their papers on "The Spectra of the Elements" that the distances of the pairs of lines within a group of chemically related elements increase in a regular way with the atomic weight. They state for the alkalies that the atomic weight is very nearly proportional to the square root of the distance. We would call attention to the fact that for the other group in which pairs of lines have been observed, the relationship between of the pair and the atomic weight may be represented by a simple formula, viz.:

In every group of chemically related elements the atomic weight is proportional to some power of the distance of the two lines of the pairs.

In general the exponent is not a whole number.

Expressed in other words this formula becomes:

If the logarithms of the atomic weight and distance be taken as co-ordinates, the corresponding points of a group of chemically related elements will lie in a straight line.

This law is shown in the two following figures. We see from Fig. 1 that among the alkalies, potassium is the only one which falls below the straight line through the remaining points. We would not here assert that the observed atomic weight of potassium is incorrect; but it seems to us interesting that this law of the straight line exhibits a larger deviation for just that element which is anomalous in respect to the periodic series, in so far as the atomic weight of *K* would have to be greater than that of argon in order to fit into the periodic series. As regards boron, gallium, and indium, the pairs of lines have not been investigated in a magnetic field. We cannot, however, doubt the

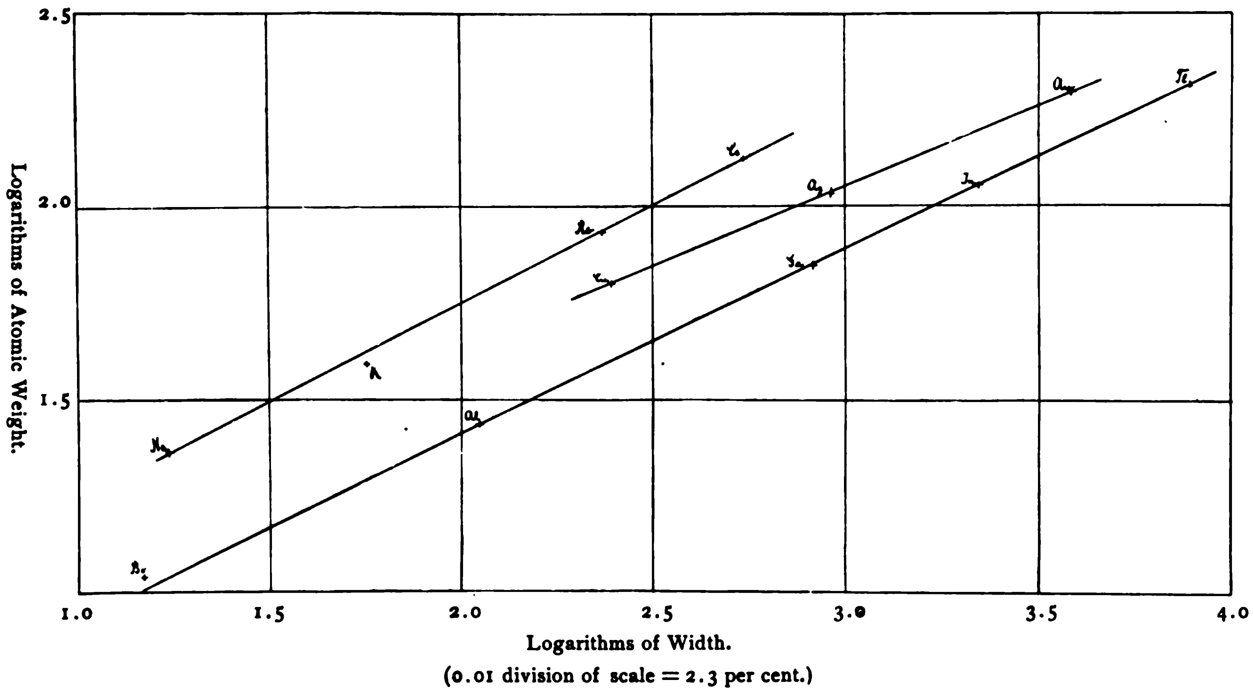
2.5
2.0
1.5
Logarithms of Atomic Weight.
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Logarithms of Width.
(0.01 division of scale = 2.3 per cent.)

FIG. 1.

existence of the corresponding pairs. The same is true of the alkalies, where only the yellow lines of sodium have been investigated in a magnetic field.

Fig. 2 represents the same relationship for *Mg*, *Ca*, *Sr*, *Ba*, and *Ra*. Extrapolation gives 258 for the atomic weight of radium. We can, of course, somewhat displace and rotate the straight line without removing it too far from the points, but the figure clearly shows that the value 225 determined by Madame Curie is decidedly off the line.

In the following table the straight line is replaced by a formula and the extrapolation by computation. If x denote the separation of the pair on the scale of vibration numbers, $\times \frac{10^8}{\lambda}$, we have:

Atomic weight = No. whose log is $(0.2005 + 0.5997 \log x.)$

	ATOMIC WEIGHT	
	By Formula	Observed
Mg	23.84	24.36
Ca	40.6	40.1
Sr	87.5	87.6
Ba	136.9	137.4

Extrapolation for radium gives:

Computed atomic weight of radium = 257.8.

We cannot risk the assertion that our figure deserves more confidence than the value determined by Madame Curie, but it should nevertheless be said that, in view of the close relationship between barium and radium, and of the small quantities of the substance with which the chemists are obliged to work, the complete separation of these two substances is very difficult; and further, that with an imperfect separation Madame Curie would necessarily obtain too small an atomic weight.

According to crystallographic observations soon to be published by F. Rinne, the bromides of radium and barium are isomorphous with each other, so that it is very probable that the two substances would crystallize together (in an isomorphous

The radium line at λ4826.14, which is the most conspicuous in the Bunsen flame, is in respect to the separation in the magnetic field analogous to the strongest line in the Bunsen flame, *Ba* λ5535, *Sr*.λ4607, *Ca* λ4246. All these lines separate into three components which for all these elements are equally separated from each other on the scale of vibration numbers.

Physikalisches Institut der Technischen Hochschule,
Hannover, Germany, January 1903.

NOTE ON SOME EFFECTS OF RULING ERRORS IN GRATING SPECTRA.

By A. S. KING.

THE possibility that errors of ruling in diffraction gratings may produce "ghosts" near strong lines in the spectrum makes it desirable that we understand as fully as possible the forms that such ghosts may take. If they occur in the most frequent form, as two lines symmetrically placed with respect to the primary line and close to this line, they are readily recognized. The writer has observed, however, that a very good grating may give, in certain regions of the spectrum, ghosts of higher order at such distances from the primary line that they might easily be mistaken for real lines.

The theory of ruling errors is a complex one. The most complete treatment we have is that given by Rowland in his article entitled "Gratings in Theory and Practice."[1] In this Rowland establishes general relations as to position and intensity of ghosts, and develops in some detail the expressions for intensity of ghosts of different orders resulting from small periodic errors of ruling. He also calls attention to other effects which may result from special conditions.

The fundamental formulæ give the position of the ghost of nth order by the relation $\mu_n = 2\pi N/ba_0 \pm ne_1/ba_0$, and the intensity by the function $J_n^2\,(b\mu_n a_1)$, where the first term of μ_n gives the position of the primary line, and the second term the position of the ghost with respect to the primary line. N denotes the order of spectrum, a_0 the grating space, a_1 and e_1 the amplitude and period of ruling error, and $b = 2\pi/\lambda$. In accordance with these relations, we have the following characteristics of ghosts:

1. Ghosts of the same order are at equal distances on each side of the primary line, and of equal intensity.

2. The distance of a ghost from the primary line varies

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[1] *Astronomy and Astro-Physics*, 12, 129, 1893.

directly with the wave-length, but is *independent of the order of the spectrum*, since the second term in the value of μ_n does not contain N.

3. The ghosts of different orders are equally spaced.

4. The intensity increases rapidly with the order of the spectrum and with the amount of ruling error.

5. The intensity of the primary line is diminished by an amount equal to the sum of intensities of the ghosts.

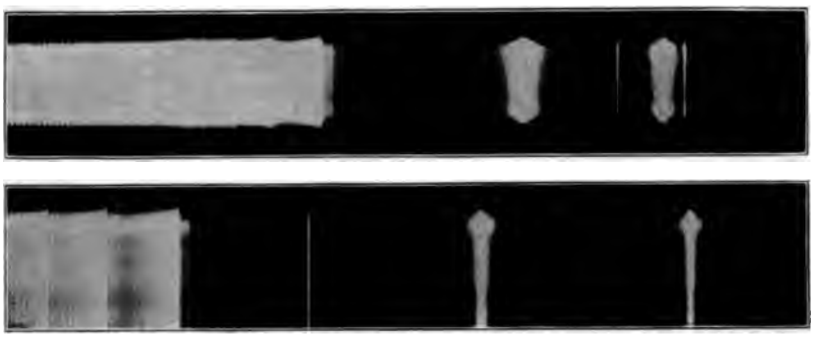
6. Since, for the same order of spectrum, the relative intensity of any ghost depends upon the value of a_1 in the expression $J^2_n(b\mu_n a_1)$, we may have the greatest intensity in a ghost of higher order than the first.

7. As $\mu = \sin\alpha$, these relations are constant only for a given position of the grating, and we have a new set of values when the angle of incidence is changed, as when we move the grating in order to observe another part of the spectrum.

The writer has recently obtained some photographs which show very clearly the effects of the last two determining elements given above. The concave grating used was one of 15 feet radius and 15,000 lines to the inch. In the first-order spectrum a prolonged exposure is required to show any ghosts on the photographic plate. On such over-exposed plates a faint appearance resembling the head of a band is seen at wave-length λ3888.75, which the writer tried in vain to identify with any known element of the spectrum, and which proves to be a first-order ghost of the λ3883 cyanogen band. Faint ghosts also appear beside very strong metallic lines, as the strontium line at λ4215.

In the second- and third-order spectra, however, remarkable series of ghosts appear above each of the cyanogen bands at λ3590, 3883, and 4216, and also near strong metallic lines in that region, as the H and K lines and the strontium line above mentioned. In each of these cases we have very distinct ghosts up to the fourth order, giving above each of the cyanogen bands the appearance of a second band with four equally spaced heads. Furthermore, the intensity of these ghosts does not diminish uniformly as they recede from the primary line. Those belonging to the head of the 3883 band occur at λ3888.75,

PLATE XVI.



Ghosts in Grating Spectra.

3893.90, 3899.06, 3904.22, and have intensities in about the ratio 10, 5, 2, and 8. The ghost of fourth order is thus almost as strong as that of first order. The heads of the bands at λ3590 and λ4216 have ghosts of similar appearance, the spacing in each case being proportional to the wave-length. Photographs of these bands in the third-order spectrum show the ghosts much stronger than in the second order, but each series preserves the same relative intensities among the ghosts of different orders, and the spacing of corresponding series of ghosts in the two spectra is exactly the same; this last fact proving conclusively that they are ghosts.

The plate shows the second- and third-order spectra in the region of wave-length λ3900, giving the head of the 3883 cyanogen band and the H and K lines of calcium, with their attendant ghosts. The ghosts of the H and K lines are faint in the reproduction, the ghost of third order being scarcely visible, but the fourth-order ghosts of the K line, reversed like the primary line, can be seen at wave-length 3926.81 and 3940.85. A remarkable feature is that the fourth-order ghost of the K line below the primary line is considerably stronger than the corresponding ghost above the line. This difference shows very distinctly in the negative, and is not in accordance with the theory of equal intensity in ghosts of the same order. Whether such a difference also exists in the ghosts of the cyanogen bands cannot be determined on account of the dense structure below the head. The plate shows the equal spacing of ghosts and the unequal dispersion of true lines in the two orders of spectra.

The writer has been unable to obtain ghosts of higher order than the first on plates taken in the region of wave-length greater than 4600, which shows that a change in the angle of incidence may produce important changes in the character of the ghosts. Prolonged exposures in the upper part of the second- and third-order spectra give first-order ghosts of considerable intensity near all strong metallic lines and carbon bands, but no ghosts of higher order can be distinguished.

The simplest method of detecting ghosts, and perhaps the only really decisive test is to photograph the suspected lines in spectra of different orders. If they are ghosts, the spacing will be the same in the two orders; while real spectral lines will suffer a dispersion proportional to the order of spectra used.

The theory of ruling errors as given by Rowland explains the action of only the principal causes of ghosts. Other causes, as periodic variation in the depth of ruling, periodic waves in the surface, and perhaps changes in the shape of the groove made by the ruling point, may all give effects whose exact nature is not easily determined. For example, the variation of intensity among the ghosts of different orders shown on my plates does not agree with any case in Rowland's table giving the distribution of intensity among the ghosts according to the amount of ruling error. It is probable that other causes have a part in producing the effects observed. However, the general effect is predicted by Rowland's theory, and the results show that ghosts need not be of any fixed type, nor of the same appearance throughout the spectrum. The fact that the grating may give ghosts of higher order at a considerable distance from the primary line (7.02 tenth-meters in the case of the K line) and more intense than those nearer the line, shows the need of care, especially in working with spectra of second or third order, that such widely separated ghosts are not mistaken for actual spectral lines. Photographs taken in spectra of different orders will at once decide this point.

UNIVERSITY OF CALIFORNIA,
February 1903.

ε *AURIGAE* A SPECTROSCOPIC BINARY.[1]

By H. C. VOGEL.

IN his investigations made a few years ago on the more refrangible parts of stellar spectra, Dr. Eberhard was struck by the fact that in the spectrum of the well-known variable ε *Aurigae*, which lies in the transition between types I and II, the series of hydrogen lines clearly extended farther beyond the H and K lines than is the case with stars of similar type. He suspected that the spectrum of the star should be regarded as the superposition of two spectra of different types.

Changes in the spectrum great enough to be recognized with the slight dispersion of the single prism spectrograph (*D*) used by Dr. Eberhard were not exhibited by plates taken at various times.

In the latter part of April and beginning of May, 1900, three spectrograms were obtained by Professor Hartmann with the large spectrograph (III) in connection with the 80 cm refractor, but a comparison of these plates in the region from λ415 to λ455 showed nothing striking. On November 9, 1901, and November 18, 19, and 22, 1902, Dr. Eberhard further photographed the spectrum of ε *Aurigae* with the three-prism spectrograph (IV) designed by me three years ago for the photographic refractor of 32.5 cm aperture. A superficial comparison of the spectra taken in the latter year with those of the preceding year was sufficient to show that the spectrum had undergone a change. The thorough examination and measurement of the spectrograms which I at once began has so far furnished the result that the suspicions of Dr. Eberhard were well founded, and that the spectrum of ε *Aurigae* is in fact the result of the superposition of two spectra, the one similar to that of *α Cygni*, and the other lying between the first and second types, like *α Persei* or *γ Cygni*.

At present the first-named spectrum is the more intense and

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[1] Translated from advance proofs, furnished by the author, of a paper communicated to the *Kgl. Akademie der Wiss. zu Berlin.*

it is displaced relatively to the other toward the violet by an amount which would correspond to a velocity of from 30 to 40 km per second. The spectrum is now distinguished from that of the previous year principally by the fact that but few lines of the iron spectrum are recognizable in it. Most of the lines have disappeared, probably as a consequence of the relative displacement of the spectra, and practically the only lines recognizable are those of the spectrum similar to *α Cygni*. Most of these appear double and are characterized by the fact that the component lying toward the violet is with few exceptions the stronger, and the boundary on the violet side of the double lines, which are often difficult to separate, is extremely sharp. This is particularly striking in case of the hydrogen lines, as is shown by a very successful plate taken by Professor Hartmann at my request on November 22, 1902, with the one-prism spectrograph (I) in connection with the 80 cm refractor.

There can accordingly be no doubt that ε Aurigae is a spectroscopic binary and probably one of very long period.

Considerable difficulties have been encountered in the comparison and measurements of the spectra because of the complications which result from dissimilarity of the superposed spectra, particularly in certain parts of the spectrum. I intend to communicate later more fully the very interesting details as to the spectrum of this star, which will be regularly observed here.

POTSDAM,
December 1902.

MINOR CONTRIBUTIONS AND NOTES.

TRANSPARENCY OF COMET 1902 *b*.[1]

THE statement is frequently made that comets are perfectly transparent, even faint stars being visible through them. The observations on which this statement is based appear to be very vague, as, even if careful comparisons were made, large errors might be introduced by the effect of the bright background formed by the light of the comet. The rapid motion of Comet 1902 *b* caused it to cover a large area, and therefore rendered it easier to find a star over which it would pass. After waiting for a suitable occasion, the observations given in Table I were made by Professor O. C. Wendell with the polarizing photometer attached to the 15-inch equatorial. On the evening of October 14, 1902, the comet passed within about 1′ of the star +21°3483, photometric magnitude 7.12. This star was compared with +21°3484, magnitude 8.19. Each set of observations was the mean of sixteen settings. The Greenwich Mean Time is given in the first column, the difference in magnitude of the two stars in the second, and the deviation of this magnitude from the mean value, 1.07, in the third column. A positive sign indicates that the star +21°3483 was faint, a negative sign that it was bright. The fourth column gives the distance of the nucleus of the comet from the star. The diameter of the coma was

TABLE I.

OBSERVATIONS.

G. M. T.	Difference	Residuals	Distance
h. m.			′
13 22.5	1.06	+.01	2.0
13 33.3	1.03	+.04	1.1
13 44.7	1.10	−.03	2.0
13 57.7	1.07	.00	4.0
14 10.8	1.06	+.01	5.5
14 26.7	1.06	+.01	7.9
14 46.9	1.08	−.01	11.0
15 2.3	1.12	−.05	13.1

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[1] From *Harvard College Observatory Circular* No. 68.

about five or six minutes. The star was, therefore, covered by it in the first three observations. The nucleus resembled a star of about the tenth magnitude and the brightness of the coma was about that of a star of the ninth magnitude when spread over a circle one minute in diameter. The largest residual —0.05 is the last one, when the altitude of the comet was only 22°. The mean of all the residuals is ±0.02. It appears, therefore, that the absorption of the light by the comet, if any, is insensible, and probably does not exceed one or two hundredths of a magnitude.

EDWARD C. PICKERING.

ADDITIONAL STARS OF THE *ORION* TYPE WHOSE RADIAL VELOCITIES VARY.

SPECTROGRAMS taken with the Bruce spectrograph since our communication in the March number of this JOURNAL show that the radial velocities of τ *Tauri* and ψ *Orionis* vary through a wide range.

In order to reach fainter spectra than can be photographed with the use of the cameras A and B, we have lately been experimenting with lenses of shorter focus (8 to 12 in. = 20 to 30 cm), with encouraging results. Several of the best types of modern anastigmat lenses have been loaned to us for trial by their manufacturers or agents. These show a great gain in the reduction of the exposure time, and it seems likely that with a camera lens of about 10.5 inches (267 mm) focus, especially constructed for our purpose, this result may be obtained without a greater loss of accuracy in the settings than would be justified under some circumstances. Pending the procurement of such a lens, the Bausch & Lomb Optical Co., of Rochester, N. Y., has most kindly allowed us to retain the "Unar" lens, Series I*b*, No. 7, which proved the most satisfactory for our purposes of all these lenses tried in connection with the spectrograph.

With this camera lens we have obtained plates of τ *Tauri* ($\alpha = 4^h\ 36^m$; $\delta = +22°\ 46'$; Magnitude, *H. P.*, = 4.4) on three dates: 1903, February 25, 26, and March 5. The first plate gave a radial velocity of about +70 km, which, in view of the usually small values for stars of the *Orion* type, was strongly suggestive of a variation. The other two plates confirm this, and show a total range of about 75 km.

Three plates have also been obtained of ψ *Orionis* ($\alpha = 5^h\ 22^m$; $\delta = +3°\ 1'$; Magnitude, *H. P.*, = 4.7), the first with the short focus camera and the other two with camera A. The examination of the first A plate indicated a high positive velocity, which led to the measurement of the short focus plate previously obtained, on which accordant values were deduced from different lines, although the C plate should necessarily be given less weight than the A plate.

The data so far secured follow:

Plate	Date	Taken by	Velocity	No. of lines	Measured by
C 17	1903, February 4	F.	−122	3	A.
A 406	February 18	F.	+148	4	F.
A 415	March 12	F.	− 31	2	F.

It would seem probable that this star will show a very large total range when observations have been secured of its maximum and minimum radial velocities. Plates of other stars of the *Orion* type taken with the short-focus camera suggest variation, but we are not at this time prepared to report as to them.

Several plates have been obtained with the longer cameras of the star η *Hydrae* (also of Type I *b*) which cause us to have suspicions as to the constancy of its radial velocity. The spectrum is very difficult of measurement, owing to the diffuseness of the lines, and we shall follow it further.

EDWIN B. FROST and WALTER S. ADAMS.

YERKES OBSERVATORY,
March 16, 1903.

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IN order to establish a permanent memorial of the late Professor Rowland, and to promote the efficiency of the Physical Laboratory of the Johns Hopkins University, one of its former students has given a most generous sum of money with which to found a special collection of books, pamphlets, and other publications in the field of radiation and spectroscopy. This is to be called the "Henry A. Rowland Memorial Library," and is to be placed in the Physical Laboratory of the University. Mrs. Rowland has given the library all those books and pamphlets belonging to Professor Rowland, which refer to spectroscopy.

To make the collection complete, and to maintain its usefulness, the co-operation of observatories, laboratories, and investigators is necessary. It is earnestly hoped that sets of official publications, books, reprints of papers on spectroscopy or allied subjects, and photographs of spectra and of apparatus will be contributed to the library, both now and in the future.

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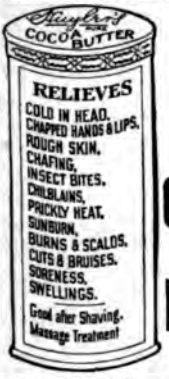

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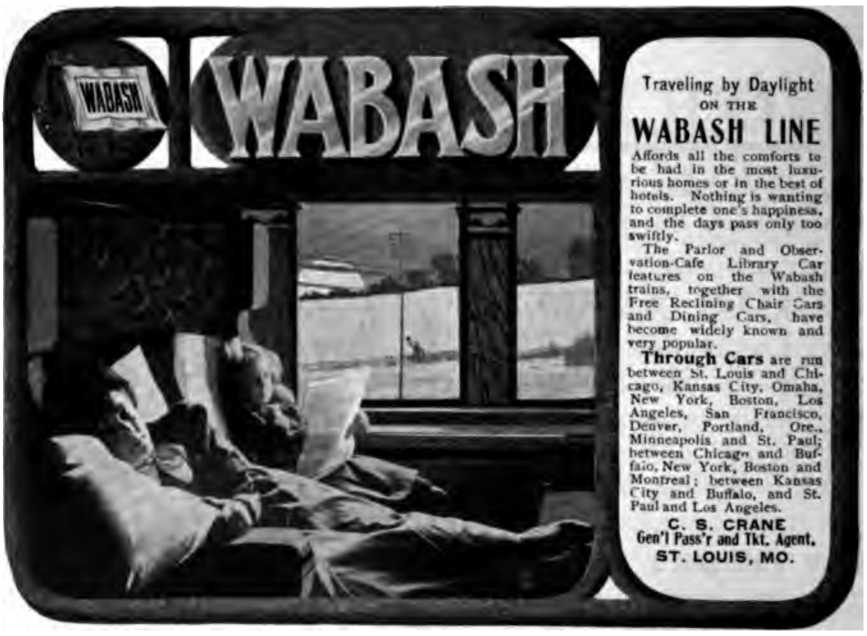

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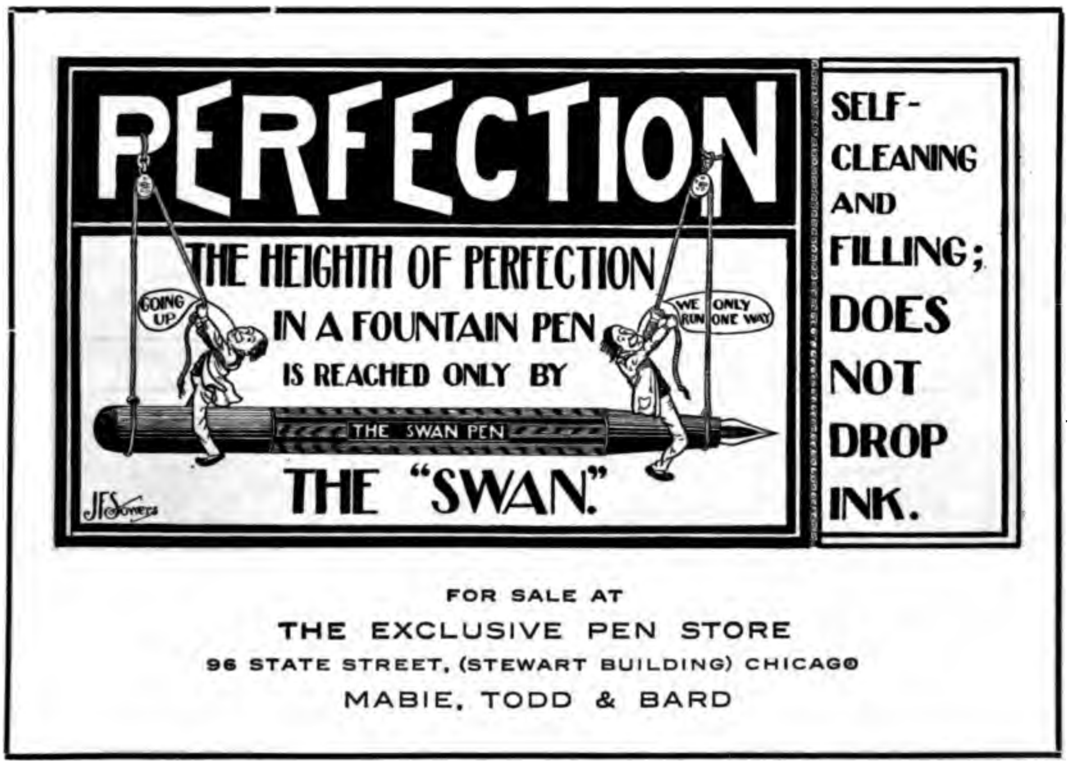

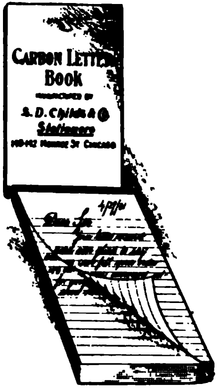
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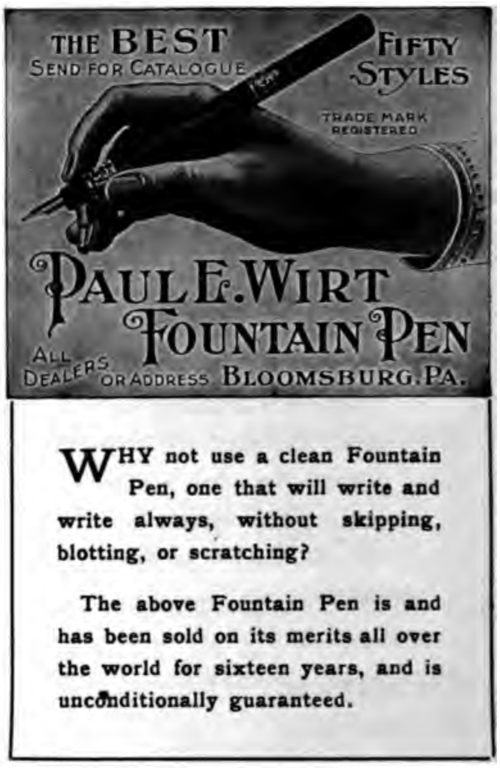

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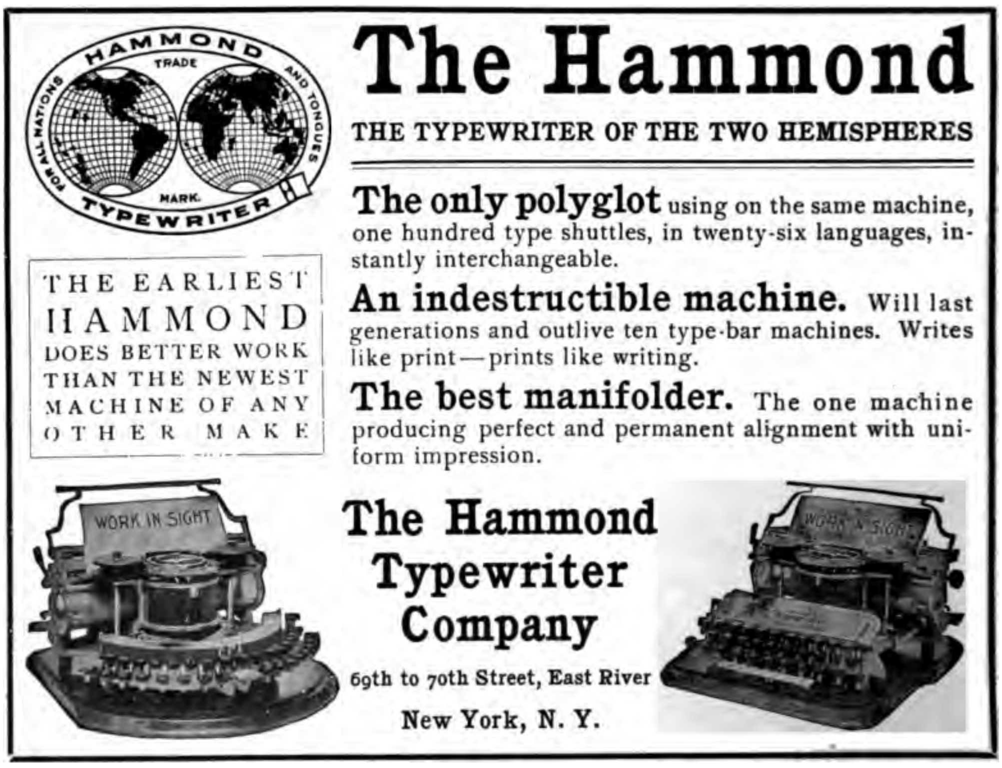

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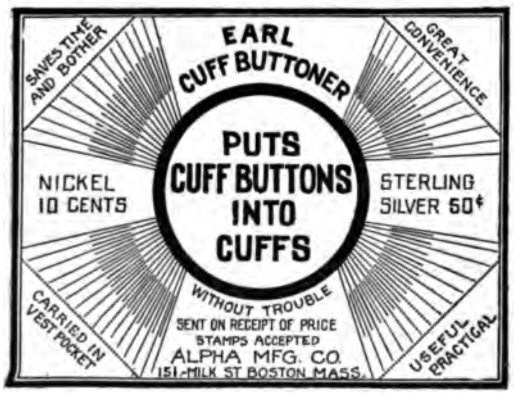

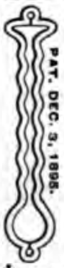

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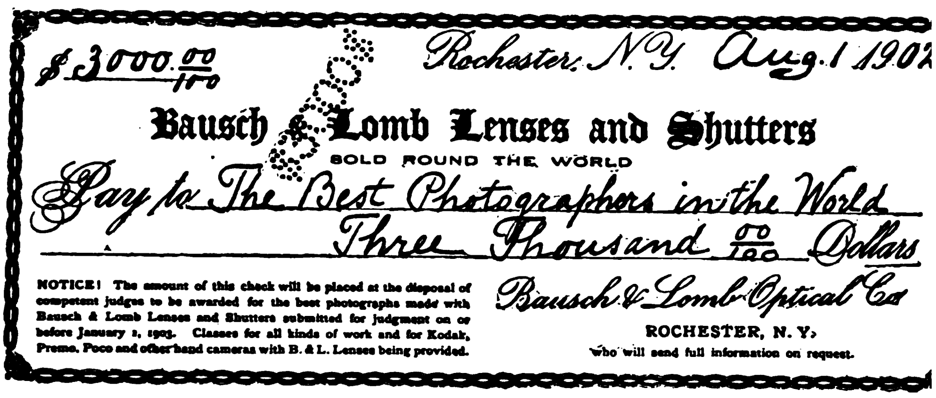

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VOLUME XVII

NUMBER

THE ASTROPHYSICAL JOURNAL

An International Review of Spectroscopy and Astronomical Physics

EDITED BY
GEORGE E. HALE AND EDWIN B. FROST
of the Yerkes Observatory

MAY 1903

CONTENTS

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AN INTERNATIONAL REVIEW OF SPECTROSCOPY
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VOL. XVII MAY 1903 NO. 4

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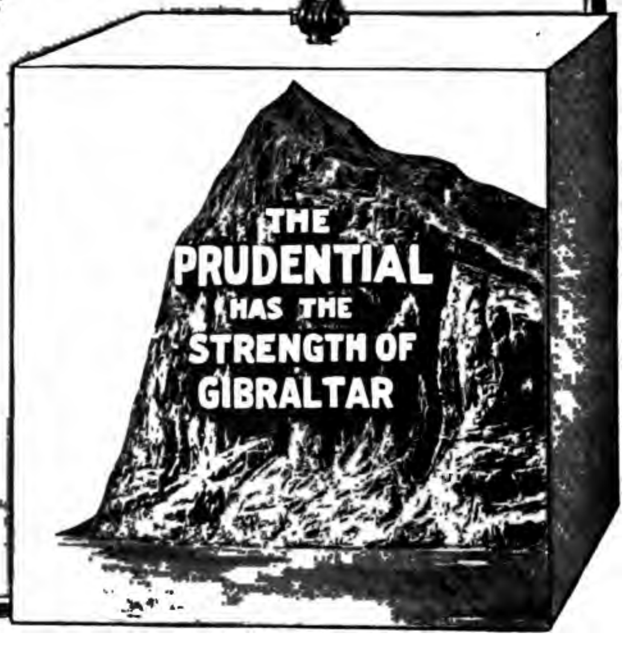

THE
PRUDENTIAL
HAS THE
STRENGTH OF
GIBRALTAR

PLATE XVII.

Mars.

September 2, 1894. λ = 100°.
36-inch refractor of Lick Observatory.

THE

ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME XVII MAY 1903 NUMBER 4

THE SOUTH POLAR CAP OF *MARS*.

By E. E. Barnard.

However much the general surface features of *Mars* may be misrepresented, and however much the canals, single and double, may be illusory, the polar caps seem to have escaped this general deluge of uncertainty and misrepresentation.

They stand for their face value, whatever may be their composition. There seems yet no definite proof that they are not as much ice and snow as that with which we have to deal in our own terrestrial winters. So much is at least suggested by the great seasonal changes they undergo from winter to summer.

The south polar cap is the better known of the two, because of its more favorable position for observation at the near approaches of *Mars*. The changes in its dimensions have been recognized since the earliest telescopic observations of the planet, and the early supposition that they were due to accumulations of snow during the winters of *Mars*, which melted away at the approach of summer, is as good a theory as any of those put forward today to explain the phenomenon.

During the close approach of *Mars* in 1892 and 1894 the writer had a good opportunity to study the planet at the Lick

Observatory with the 12-inch and 36-inch refractors. A carefu series of drawings was made at that time, but they have not yet been published.

Struck with the great changes that take place in the polar caps, I decided to make a series of micrometer measures of the south cap, instead of remaining content with estimates and drawings of the phenomenon, though a great number of drawings were made of the cap—some sixty of which were published in *Popular Astronomy* for June 1895 (**2**, 433–443).

It would seem that the changes in the dimensions of these caps have always been studied from drawings and never from a systematic series of micrometer measures. While these changes can be fairly studied from careful drawings, there must always remain a large percentage of uncertainty, especially if the drawings are by different observers; careful micrometer measures are therefore always to be preferred, as changes indicated by them can be relied upon.

Following are the measures of the cap at the oppositions of 1892 and 1894. The time is 8^h 0^m slow of Greenwich. The column headed "Days" is the number of days before or after the summer solstice of the southern hemisphere of *Mars*. The measured diameter is given under the heading "Observed, while the values under "MΔ" are the diameters reduced to the mean distance of *Mars* = 1.52369. Under the head "Residuals" the difference of each observation from the curve is given.

1892.

(Made with the 12-inch refractor.)

Date		Days	Observed	MΔ	Residuals
July	3^d 15^h 25^m....	−102	$9'.31$	$2'.78$	$-0'.12$
	8 13 11	97	10.08	3.06	+0.20
	15 12 55	90	9.97	2.67	−0.05
	22 13 35	83	9.90	2.52	−0.05
	31 12 40	74	10.02	2.49	+0.19
August	2 11 20	72	8.76	2.17	−0.10
	3 11 0	71	8.50	1.75	−0.13
	3 13 40	71	8.86	2.10	−0.42
	4 11 50	70	8.48	2.10	−0.11
	5 11 45	69	8.70	2.16	0.00
	7 11 25	67	8.17	2.02	−0.07

1892.—*Continued.*

(Made with the 12-inch refractor.)

Date	Days	Observed	M Δ	Residuals
8 10 35	−66	8.75	2.17	+0.10
9 11 30	65	8.38	2.08	+0.05
10 10 30	64	7.91	1.96	0.00
11 12 20	63	7.89	1.98	+0.01
12 11 40	62	7.99	1.99	+0.06
14 10 42	60	7.93	1.99	+0.11
17 9 30	57	6.59	1.67	−0.05
18 12 5	56	7.13	1.79	+0.07
19 12 35	55	7.13	1.82	+0.12
21 11 45	53	6.71	1.73	+0.17
23 9 42	51	6.73	1.75	+0.20
September 2 10 10	41	3.62	1.01	−0.25
4 7 50	39	3.80	1.08	−0.12
6 9 30	37	2.81	0.81	−0.35
8 8 6	35	4.44	1.11	0.00
9 8 22	34	3.54	1.05	−0.06
9 11 0	34	3.65	1.08	−0.05
11 8 25	32	3.45	1.04	+0.05
16 7 40	27	3.75	1.19	+0.22
19 8 20	24	2.95	0.96	+0.08
22 6 50	21	2.94	0.99	+0.15
23 7 30	20	2.12	0.72	−0.14
October 7 7 27	− 6	1.82	0.71	+0.07
November 6 6 20	+24	0.60	0.31	−0.07

1894.

(Made with the 36-inch refractor.)

Date	Days	Observed	M Δ	Residuals
May 21d 16h 1m	−103	3″.84	2″.79	−0″.02
28 16 0	96	3.66	2.58	−0.10
June 11 16 0	82	3.81	2.46	+0.07
18 15 20	75	3.69	2.28	0.00
24 15 50	69	3.55	2.10	−0.02
25 15 25	68	3.71	2.18	+0.06
July 1 16 0	62	3.66	2.07	+0.15
8 16 30	55	3.56	1.92	+0.22
15 15 5	48	2.25	1.15	−0.35
30 13 50	33	2.99	1.37	+0.19
August 5 16 50	27	2.16	0.94	−0.11
6 13 40	26	2.24	0.97	−0.05
13 17 55	19	2.95	1.21	+0.28
26 13 55	− 6	1.65	0.61	−0.10
September 2 12 30	+ 1	2.17	0.76	+0.12
9 12 10	8	1.52	0.50	−0.09
16 14 45	15	1.75	0.55	+0.02
30 11 10	29	1.14	0.33	−0.02
October 7 9 40	36	1.43	0.41	+0.05
8 10 30	37	1.49	0.42	+0.06
November 11 9 35	71	0.33	0.11	−0.10

In recently looking over these measures of the south polar cap, it occurred to me that if they were plotted with respect to the summer solstice of the Southern Hemisphere of *Mars*, and if curves were drawn through them, the results might be very instructive. The two curves that accompany this paper have therefore been prepared in that manner.

The measures are all reduced to the mean distance of *Mars*, and hence are strictly comparable. In the diagrams the vertical scale represents the diameter of the cap in seconds of arc, while the horizontal scale gives the time in days before and after the summer solstice of the southern hemisphere of the planet.

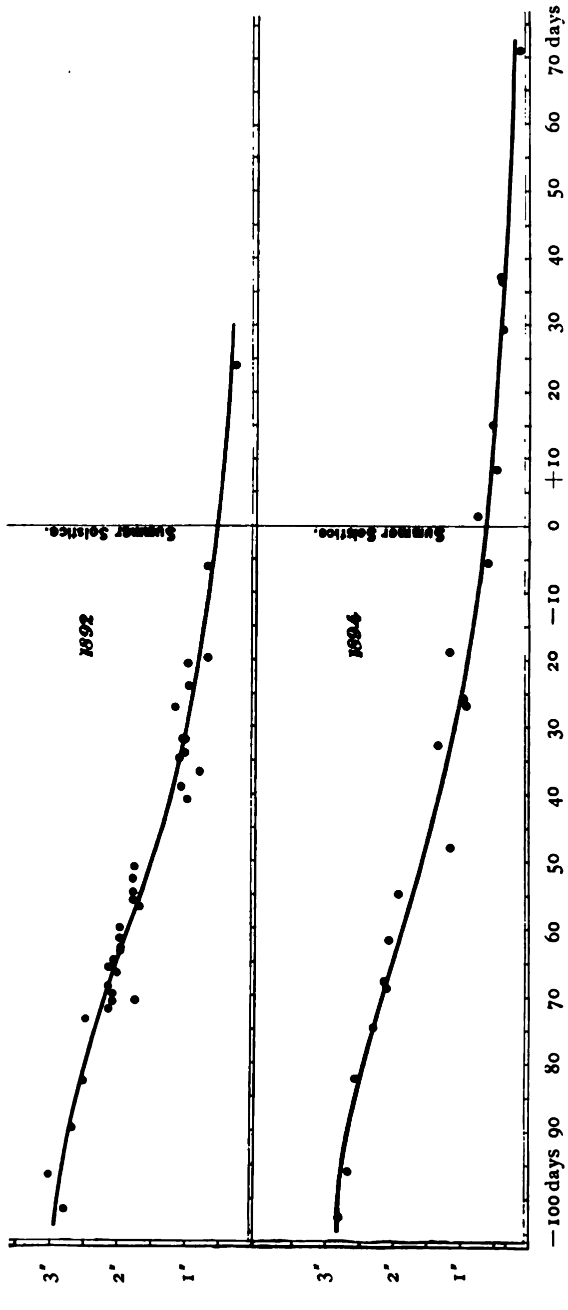
At first sight the striking fact is apparent that these two curves are parallel throughout. The cap, therefore, at both oppositions, followed the same law of decrease with surprising closeness.

Another important feature, to which I have already called attention in the number of *Popular Astronomy* referred to, is that the cap continues to diminish after the summer solstice, or beyond the time when the greatest heat is received from the Sun, showing, as in the case of the Earth, that the highest temperature is not reached until several months after the maximum of solar heat. This may have considerable bearing upon the presence of a Martian atmosphere.

There seems to be a general belief now that *Mars* certainly has an atmosphere. This atmosphere seems to be very much less dense than our own, and yet it is of sufficient density to produce the phenomena of the polar caps by condensation and evaporation, and also to produce, though rarely, some form of clouds.

The maximum diameter of the cap is perhaps shown by my measures, as the Sun had only risen on the south pole some four or five weeks earlier, and the curves do not seem to indicate that there was any sensibly larger diameter for the short interval between the rising of the Sun and the beginning of the measures.

It would be very interesting to watch the growth of the south cap to see if the increase follows the same law as the decrease.



Curves showing diminution of diameter of South Polar Cap of Mars.
Ordinates: Measured diameters of cap. Abscissae: Days before and after Martian Summer Solstice.

It seems, however, that the increase can never be seen. Though the planet was carefully watched in 1894, nothing was visible of the cap after November 19. It seemed to have entirely disappeared. Records of its non-visibility were kept as late as May 12, 1895. After the middle of February, however, it would have been immersed in the shadow, as the Sun, after that date, would pass too far north to shine on it. Hence, if we take these observations as a criterion, it will not be possible to watch the growth of any portion of the cap at any time.

On several occasions a portion of the outline of the polar cap was lost by a dusky obscuring medium which would eventually clear away and the outlines would then again become distinct. There seemed to be good reason for believing this temporary obscuration to be of the nature of clouds.

In May of 1894 the polar cap covered an area of about 365,000 square miles. By the last of November it had all disappeared, having apparently melted entirely away.

The rapid decrease of the polar cap shows that the snow, if snow it be, cannot be of great depth. It is probably a more or less thin sheeting, just as in winter here on the Earth the ground will be sometimes covered with snow down beyond middle latitudes, which may in the course of a few days melt away, producing a rapid change in the apparent extent of the Earth's polar cap as seen from, say, *Venus*.

The following table gives the diameter of the south polar cap for every five days before and after the Martian summer solstice, taken from the curves of 1892 and 1894. It will be seen that the difference is very small, not exceeding 0ʻ08. Whether the change of sign is due to a real difference in the diminishing of the cap in 1892 and 1894 it is not possible to tell—the quantity involved in the apparent change is too small to deal with in measures of this kind, and can well be attributed to errors in drawing the curves. From the strikingly close agreement of the curves at the two seasons, it would appear that the mean curve indicated in the last column would serve as a means of predicting the mean diameter of the cap with great exactness—indeed, with greater accuracy than it can be measured. Of course, this is a statement resting on only two Martian years, but I believe the changes in these caps, apparently uninterrupted by freaks of weather, and depending probably on the position of the Sun alone, follow a perfectly regular law which is shown by these curves, and which permits an accurate prediction of the mean diameter of the cap.

DIAMETER OF THE SOUTH POLAR CAP FOR EVERY FIVE DAYS, TAKEN FROM THE CURVES OF 1892 AND 1894.

No. Days before Summer Solstice	1892	1894	Difference	Mean Curve
100	2′.90	2′.85	+0′.05	2′.87
95	2.83	2.77	+0.06	2.80
90	2.74	2.70	+0.04	2.72
85	2.61	2.57	+0.04	2.59
80	2.50	2.42	+0.08	2.46
75	2.35	2.31	+0.04	2.33
70	2.20	2.17	+0.03	2.19
65	2.04	2.01	+0.03	2.02
60	1.86	1.87	−0.01	1.87
55	1.69	1.73	−0.04	1.71
50	1.53	1.56	−0.03	1.54
45	1.37	1.43	−0.06	1.40
40	1.24	1.30	−0.06	1.27
35	1.12	1.20	−0.08	1.16
30	1.02	1.09	−0.07	1.06
25	0.94	0.98	−0.04	0.96
20	0.84	0.91	−0.07	0.88
15	0.77	0.82	−0.05	0.80
10	0.70	0.75	−0.05	0.73
5	0.64	0.68	−0.04	0.66
0	0.58	0.63	−0.05	0.60
After 5	0.52	0.60	−0.08	0.56
10	0.48	0.56	−0.08	0.52
15	0.44	0.52	−0.08	0.48
20	0.41	0.49	−0.08	0.45
25	0.37	0.45	−0.08	0.41
30	0.35	0.42	−0.07	0.39
35		0.39		
40		0.35		
45		0.32		
50		0.30		
55		0.27		
60		0.25		
65		0.24		
70		0.23		

The outline of the polar cap was often irregular. Details were frequently visible upon its surface in the form of bright spots, broad bright lines, and changing dark spots. A large temporary dark spot was visible near the middle of the cap at both oppositions when the cap was at its largest. This seemed to disappear as the cap became smaller. On one occasion this central marking on the cap was of a reddish hue, like the general surface of the planet, and on several dates the cap was distinctly double.

The most striking phenomenon connected with the cap, however, and perhaps the most important, was the recurrence of a projection from the edge of the cap, which appeared at the same point in both years, and which was left behind as a bright strip as the cap diminished, showing it to be due to some local peculiarity of the surface of *Mars*. It was suggested at the time that this might be caused by a group or range of mountains at that point on *Mars*. If these were mountains, the snow on their summits would remain stationary as a white strip, after the receding cap had left it, until it melted. Thus the decay of the polar cap probably reveals to us the existence of mountains on *Mars*, which would otherwise remain unknown.

In tracing back this phenomenon through former oppositions it was found that this very thing had been seen by Mitchel at Cincinnati in the year 1845 at the same point on the surface of *Mars*. It doubtless repeats itself every Martian year when the cap is diminishing.

It is possible to predict when it will be visible from the Earth. It begins to appear about sixty days before the Martian summer solstice, and is passing through its changes for about a month. It ought to begin to be visible when the heliocentric longitude of *Mars* is about 320°. When more careful and continuous observations have been secured, its reappearance ought to be predicted very closely.

Since writing the above I have consulted the classical paper by Mr. N. E. Green in the *Memoirs of the Royal Astronomical Society*, Vol. XLII, where he has given a series of twelve admirable drawings of *Mars*[1] (made at Madeira in 1877), with a map

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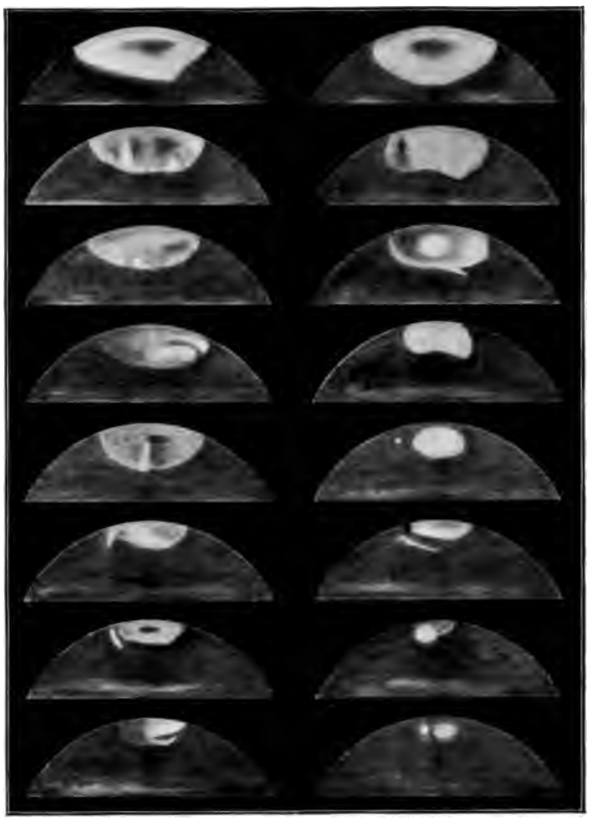
[1] Mr. Green mentions that these twelve are selected from forty-one drawings of the planet made by him in 1877. These splendid drawings, which so faithfully represent the telescopic appearance of *Mars*, should all be made available to those interested in the planet. In these days of half-tone work their accurate reproduction would be inexpensive.

PLATE XVIII.



THE SOUTH POLAR CAP OF MARS.

of the surface of the planet. In his paper Mr. Green calls attention to the repetition of the projection from the south polar cap (the same shown in my drawings) and offers the same explanation for its cause, *i. e.*, a mountainous surface. One of these bright spots he has named "Mitchel Mount," in honor of Mitchel, of the Cincinnati Observatory, to whose drawings we have referred.

The north cap in 1895 was well seen, clear, and distinct on May 6. Evidences of it had been seen several months earlier. A note on December 23, 1894, at 6^h says: "there is a strong bluish white glow at the north limb, but no definite polar cap." This glow was frequently noticed thereafter until the true cap made its appearance.

To show some of the peculiarities of the outlines of the cap and of thedet ails upon its surface, eight drawings for each of the seasons, 1892 and 1894, have been selected for reproduction here (Plate XVIII). No effort has been made to retain any of the details of the surface of the planet near the caps, as such details would more properly belong to the drawings of the planet itself.

One drawing of the planet is also given (Plate XVII), as a sample of the details visible in 1894. In many of the drawings secured at that opposition, when the planet was well seen, the details were so abundant and complicated, especially in the dark regions, that it was impossible to correctly delineate them.

YERKES OBSERVATORY,
April 2, 1903.

CATHODO-LUMINESCENCE AND THE NEGATIVE POLE SPECTRUM OF NITROGEN.

By PERCIVAL LEWIS.

I. A STUDY OF THE NEGATIVE GLOW.

IN a previous paper[1] it was shown that the vapors of a number of metals can be made luminous by the action of cathode rays alone, precautions being taken to prevent the passage of a conduction current through them. It has been suggested by several investigators that the characteristic negative glow observed in vacuum tubes containing certain gases, notably nitrogen, is likewise the direct effect of the energy absorbed from the cathode rays by impact or otherwise. In the case of volatile metals it is easy to isolate their heavy vapors by heating the metals at one end of a long vacuum tube. Their slow diffusibility and rapid condensation on passing beyond the heated region prevents them from raising the pressure of the highly rarified atmosphere around the distant cathode, from which the rays are projected into the mass of vapor. Such a method is obviously impossible in the case of light and rapidly diffusible gases, such as nitrogen. In such cases complete isolation from the region traversed by current can be secured only by a very thin metal partition, as in Lenard's experiments,[2] and then, as shown by Lenard, the luminosity produced is too small to be examined spectroscopically. Such luminosity does exist, however, although it cannot be positively identified with the negative glow. The only practicable method of showing that the negative glow is due altogether to cathode rays seems to be an indirect one—by comparing those parts of the negative glow through which it is likely that little or no current flows with those parts through which the greater part of the current flows. If no difference is found in the luminosity, either qualitative or quantitative, it would seem

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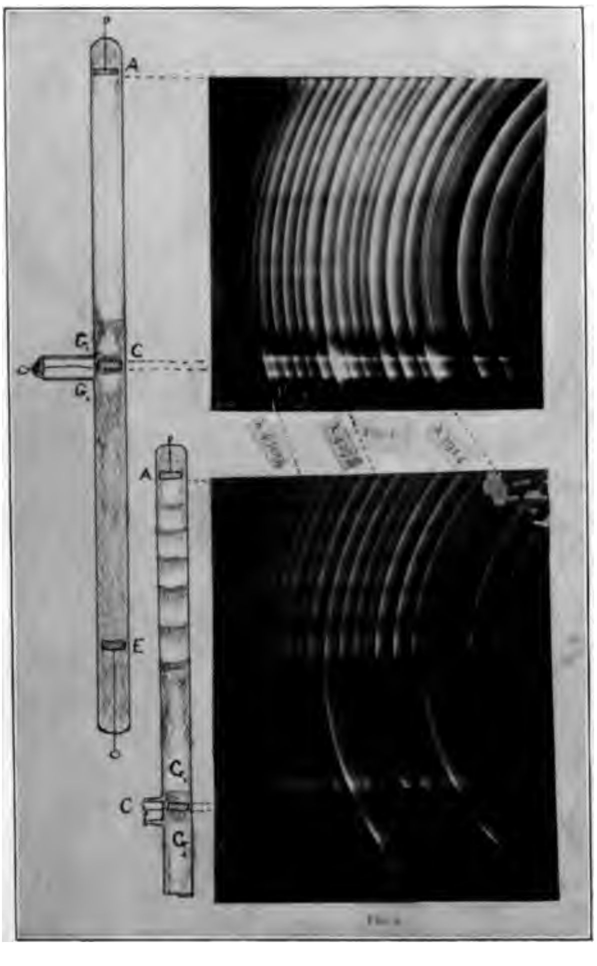
[1] P. LEWIS, ASTROPHYSICAL JOURNAL, 16, 31, 1902.

[2] *Wied. Ann.*, 51, 229, 1894.

PLATE XIX.



exceedingly probable that the luminosity in this part of the tube is due to cathode rays solely.

Since there is convincing evidence that cathode rays consist of negatively charged particles, it may be asked whether the continuous projection of such particles does not in itself constitute a convective electric current; for it is generally taken for granted that the current through the positive column is also transported convectively, by some process akin to electrolytic conduction. There are, however, at least two grounds for differentiation between the two processes: (1) the cathode discharge at low pressures takes place in all directions normal to the cathode, with absolute indifference to the position of the anode, while the positive column, like the ordinary electric current, takes the shortest or least resistant path between the electrodes; and (2) the cathode rays seem to consist of subatomic corpuscles, while such evidence as we have indicates that the positive electricity travels with particles of atomic magnitude, as in the case of electrolysis.

A straight tube of about 6 mm internal diameter was used. (See Plate XIX.) The cathode *C* was in the middle, the anode *A* near one end, and an idle electrode *E* (usually earthed through a high resistance) at the other end. The distance between the electrodes was about 7 cm. They were made of thick disks of aluminum, and nearly filled the cross-section of the tube. A Leeds induction coil giving a very heavy spark about 6 cm long was used. The nitrogen was prepared by heating a solution of ammonium sulphate and sodium nitrite in molecular proportions, and was freed from oxygen, carbon dioxide, and water vapor by passing it in succession through pyrogallic acid, concentrated potassium hydrate solution, and a train of drying tubes.

It is, of course, well known that the direction of the negative glow is independent of the position of the anode. It has not, perhaps, been sufficiently emphasized that when the cathode has sufficient free space on both sides the glow is perfectly symmetrical, and is just as large and intense on the side opposite the anode as on the same side. This is true when the cathode almost closes the tube, but not when it entirely closes it. The glow G_2 resembles G_1 in form, size, and intensity, whether all three electrodes are insulated, *A* alone earthed, or *A* insulated and *C* and *E* both earthed. The only difference observed was that at very low pressures in the latter case there was a division of the negative discharge between *C* and *E*, with a short independent positive column between them; but even in this case the discharge from *C* was perfectly symmetrical.

The luminosity of G_2 was apparently equal to that of G_1 at all pressures. This was tested by throwing an image of each in succession on the slit of a Glan spectro-photometer and measuring the intensities of the three bright negative pole bands λ 5228, λ 4709, and λ 4278 at equal distances on each side of *C* through a wide range of pressures. At low pressures and at considerable distances from the electrode the luminosity was small and measment difficult; but up to distances of 2 cm from *C* at a pressure of about 1 mm there seemed to be equality of intensity on each side, within the range of experimental error. This symmetry is also clearly shown on photographs to be described later.

With this form of tube it would certainly be incorrect to say that no conduction current passes from the anode to the farther side of the cathode, and consequently through G_2. This is shown by the fact that when *C* completely closes the tube, except for a small tortuous channel to permit equalization of gas pressure, there is no negative glow on the farther side, as there should be if the negative glow were independent of the existence of the anode within the same inclosure, as well as of its direction. The greatest resistance to the discharge is at the cathode, and at low pressures we may expect that every available part of its surface will be equally brought into requisition to facilitate the discharge, even though the diverted part of the conduction current be forced to take a very roundabout and constricted path to the rear of the cathode. It seems likely, however, that the greater part of the current will pass directly to the nearer side, and that the diverted part, after passing around the cathode, will take as short a path as possible to its surface; and yet the intensities of the negative glow on the two sides is the same not only near the cathode, but at distances as great as 2 cm. The matter is complicated by the fact that the canal rays discovered by Goldstein[1] and shown by Wien[2] to consist of projected positively charged particles, coming probably from the anode, pass readily through openings through and around the cathode, and may take some unknown part in the processes going on in that region. The canal rays, however, have not been observed at pressures of more than a few tenths of a millimeter.

In order further to vary the conditions, a completely closed wire-gauze cylinder was inserted between E and C, touching the former and ending about 5 mm from the latter. The negative glow penetrated the meshes of this cylinder, without any apparent changes of either intensity or length. In most cases C was earthed by a wire and E by contact with a wooden table, so that static discharges might escape from the latter without any appreciable conduction current.

The effects of the electrostatic forces acting between C and the gauze cylinder and the walls of the tube must not be overlooked, and there can be little doubt that some discharges through this region must have resulted from them. They were never sufficiently strong to cause visible luminosity.

Thus the currents through G_2 must have been small compared with that through G_1; furthermore, the conditions were so varied that there must have been great relative changes in the intensity of these small currents—and yet G_2 remained exactly like G_1. There seems to be no escape from the conclusion that the negative glow is independent of current and dependent upon some other form of discharge, and no alternative to fixing the responsibility upon the cathode rays.

An arrangement was next devised for photographing the spectrum of all parts of the tube simultaneously, in order that any local differences might be more clearly shown and recorded. A metallic slit about 15 cm long was placed immediately in front of the discharge tube and parallel to it. By means of two lenses of about 30 cm focal length, one simple and the other achromatic, and a large Rutherfurd compound prism, a spectrum was thrown on a photographic plate. The arrangement was

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[1] *Berichte d. k. Akad. Berlin*, 1886.

[2] *Wied. Ann.*, 65, 446, 1898.

crude, and not capable of accurate or permanent adjustment; nevertheless some of the results, especially those dependent upon altering the nature of the discharge, are, perhaps, of sufficient interest to warrant the reproduction of a few of the plates.

The principal characteristics of the spectrum of the simple induction discharge at different pressures are shown in Figs. 1 and 2, Plate XIX, corresponding to pressures of about 10 and 1 mm respectively. The wave-lengths of the principal negative pole bands are indicated, and an iron comparison spectrum is also given. Alongside of Fig. 1, is a diagram of the vacuum tube, showing the corresponding appearance of different parts of the discharge. In Fig. 1 the first dark space extends less than a millimeter from the cathode, the second is nearly a centimeter long, and the negative bands barely stretch across it. The almost perfect symmetry of the glow is well shown. It is to be noted that all the positive pole bands appear at the cathode, and are about as intense as in the positive column. They extend faintly across the second dark space, as well as the first, so that these spaces are by no means absolutely dark. Sufficient exposure would always bring out all the positive bands throughout the dark spaces.

In Fig. 2 the first dark space is several millimeters long, while the second is driven up to the positive column by the negative glow; but the strong negative pole bands run across to the anode, with uniformly diminishing intensity. Here also the negative pole bands appear to be symmetrical on both sides of the cathode, while the positive bands are somewhat stronger toward the anode. This is probably due to the fact that the discharge was not strictly uni-directional, so that feeble positive alternated with strong negative discharges from *C*. Similar effects were observed on several plates at low pressures, but not at high pressures. Several striations of the positive column are shown, with marked variations in the intensity of the positive bands, but so little in that of the negative bands that it is suggested that the latter run through the positive column without any variations except a gradual decrease of intensity, the small differences observed being due to the underlying weak positive bands. Similar effects were observed on several plates, and show that the negative glow is independent of the changes of potential gradient found in the striations and the second dark space. In the first dark space, however, the bands are somewhat weaker than they are at the beginning of the glow. It is interesting to note that the *F* line, which frequently appeared, and two strong lines which appear to be λ3962 and λ3944 the longest lines of aluminum, are strongest in the first dark space. These aluminum lines appeared on nearly all the plates, increasing in intensity as the pressure diminished, and extend, not the entire length of the negative glow, but only about as far as the "spluttering" of aluminum on the walls of the tube could be observed. This shows that the particles of metal detached from the electrode assist in the discharge, and can give a spectrum, although the contrary is sometimes assumed, and that this spectrum is probably due to aluminum in the atomic state, not in the form of cathode corpuscles, in which case the lines would extend throughout the negative glow.

II. EFFECTS DEPENDING UPON NATURE OF DISCHARGE.

It was found that some interesting changes resulted from altering the nature of the discharge, as in passing from the simple discharge to that with a spark-gap in the circuit and a condenser in parallel, or in adding self-induction to the above. Some of these effects, such as the transition from the line to the band spectrum, are well known, but others seem to have previously escaped observation.

These changes are described in detail below, with references to figures in some cases.

Pressure 100 mm (Plate XX, Fig. 3). — Simple discharge (*A*): The negative pole bands are faint and very short. The aluminum pair is absent. Self-induction (*B*):—There is a remarkable change in the appearance of the spectrum. The negative pole bands are strong across the entire field. The positive pole bands are very weak. The aluminum pair appears at both electrodes, and some faint aluminum lines at one electrode. Condenser (*C*):—The well-known line spectrum appears, with some weak bands. The aluminum pair appears, but is not so strong as with self-induction. The appearance of the condenser discharge was dazzling white; that with self-induction was a light pink.

Pressure 40 mm (Fig. 4). — Simple discharge: As in previous case, except that the negative bands are longer. Self-induction (*A*): The negative pole bands are strong across entire field, but the contrast with the positive bands is not so strong as at 100 mm. The aluminum lines were weak. Condenser: Line spectrum as before. Tesla current (*B*): Very much like spectrum with self-induction, but the negative bands are relatively a little weaker. Note that this spectrum appears identical as far as relative intensities is concerned with the condenser spectrum (*B*) of Fig. 5.

Pressure 10 mm (Fig. 5). — Simple discharge: See Fig. 1, Plate XIX. Self-induction (*A*): Like (*A*), Fig 4, except that the positive bands are possibly relatively a little stronger. Condenser (*B*): The lines have changed to bands, but the negative bands are relatively not quite so intense as with self-induction. The spectrum is like that with the Tesla current at 40 mm. The condenser current was far more intense than the Tesla current; the self-induction current was of intermediate intensity. The relative intensities of the different discharges may be inferred from the fact that usually the times of exposure with condenser, self-induction, simple, and Tesla currents were about 10 minutes, 15 minutes, 20 minutes and 1 hour respectively. Where the relative differences in the spectra are small, perhaps the best estimate may be obtained by comparing the head of λ3914 with the head of the neighboring positive band on the left. With self-induction in every case the former is more intense; with condenser or Tesla current they are about equal.

Pressure 2 mm (Fig. 6). — Appearance about as before, except that negative glow is much longer with simple discharge. Spectra with self-induction and with condenser are shown in (*A*) and (*B*). (*C*) and (*D*) will be described later.

Pressure 0.7 mm. — Simple discharge. — Negative bands run across to anode, and positive bands are very weak. Positive

PLATE XX.

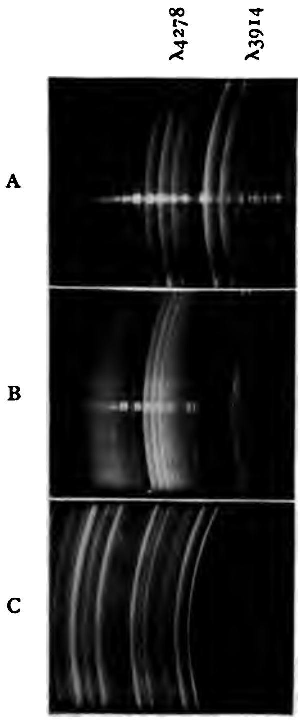

FIG. 3. P = 100 mm.

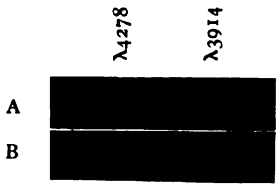

FIG. 4. P = 40.

FIG. 5. P = 10.

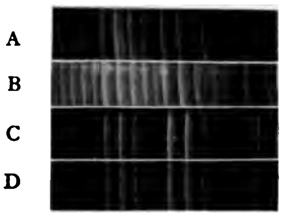

FIG. 6. P = 2.

column is about 4 mm long. The spectra with self-induction and with condenser are hardly distinguishable, and the negative bands, while present throughout tube, are hardly so intense as one would expect from their appearance with the simple discharge and the low pressure. They by no means predominate over the positive bands.

With a slowly oscillating current through a vacuum tube, such as can be obtained when a condenser, without spark-gap, is in series with the tube (in which case the frequency is twice that of the primary break) both ends of the tube give the negative glow, which is limited to the ends. The question arises: why, with very rapid oscillatory discharges, do the negative bands appear from one end to the other? Goldstein[1] noted that with very intense discharges the negative bands appeared in all parts of the tube, and he seems to have associated this effect with the intensity of the discharge. We see, however, that the spectrum of the feeble Tesla discharge at 40 mm is identical with that of the strong condenser discharge at 10 mm. (At 40 mm the condenser discharge gave a line spectrum, and at 10 mm the tube was broken before a Tesla exposure could be made, so comparison at the same pressure was not made.) In all cases there was an enhancement of the negative bands by self-induction, although this effect became small at low pressures; but the self-induction discharge is weaker than that of the condenser. The electromotive intensity of the Tesla current is greater than that of the condenser, its intensity (energy) is less, and its oscillatory frequency is of the same order. The self-induction discharge is intermediate in energy, its frequency is much less than that of either condenser or Tesla discharge. It seems that we should look for the cause of the observed differences, not to electromotive intensity or energy (although they may take a part), but in altered frequency of the discharge. Just how this time element affects the problem is next to be considered.

A clue to the cause of the presence of the negative bands through the tube, and also to the effect of self-induction, is found in two important papers by Spottiswoode and Moulton.[2] They show that,

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[1] *Berichte d. k. Akad. Berlin*, 1876 p. 281; *Wied. Ann.*, 15, 280, 1882.

[2] *Phil. Trans.*, 1879, 1880.

in general, the time required for the discharge of negative electricity from an electrode is greater than that required by positive, and that in some cases discharges may take place from parts of the inner walls of the tube under the action of strong electrostatic stresses. Later J. J. Thomson[1] showed that the positive luminosity starts at the anode, travels at a finite rate toward the cathode, and even in a long tube will arrive at a point near the cathode before the negative glow. On account of the lag in the negative discharge, the walls of the tube, on which electricity is separated inductively, may assist the cathode in neutralizing the positive electricity, and this general discharge may account for the general presence of the negative bands when intense discharges are employed. If, however, the rate of oscillation is very rapid, as in the condenser discharge, the interval between two oscillations may be too short to allow complete discharge of the negative electricity—in other words, the discharge may be, as Spottiswoode and Moulton found in some cases, almost uni-polar, taking place only from the anode, and the negative bands will be weak. On introducing self-induction the oscillations become slower and a more complete discharge of negative electricity may result, thus enhancing the negative bands. The intensity or temperature of a discharge may determine the production of a line or band spectrum, but it seems at least possible from these considerations that the appearance of the negative bands throughout the tube is only an indirect effect of the intensity, depending directly upon the cathode rays emitted from the walls of the tube under the action of electrostatic stresses. It might be anticipated that the metallic screen with slit near the tube would magnify these effects, but the same results were obtained when a slit ruled on a developed photographic plate was substituted.

If this hypothesis be correct, the action of a cathode or X-ray tube with spark-gap and condenser in parallel should be stimulated by adding self-induction. It is probably known that this is the case, although previously unknown to the writer. A test substantiated this expectation; self-induction added to the cir-

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[1] *Recent Researches in Electricity and Magnetism*, p. 116.

cuit of a cathode ray tube increased the fluorescence several times, although the spark-gap showed plainly that the intensity of the discharge was thereby diminished.

K. Wesendonck[1] showed that the walls of a vacuum tube seem to facilitate the negative discharge.

Another test was made by placing the electrodes previously used in a large glass bulb about 15 cm in diameter. The discharge through this tube was very unsteady except at pressures under 10 mm, so that it was difficult to get photographs at higher pressures. At about this pressure both the condenser and self-induction gave the continuous negative bands; but they were very feeble compared with those obtained with the small tube. At a pressure of about 2 mm the heads of the λ4278 and λ3914 bands can barely be detected in the spectrum of the condenser discharge (Fig. 6, *D*), but with self-induction they are seen faintly at the electrodes, while elsewhere there is not a trace of them to be seen (Fig. 6, *C*).

This is strong corroborative testimony, but is, of course, not absolutely conclusive as excluding the effects of intensity until we know how much the latter is modified by the size of the tube. With the large tube, however, the discharge confined itself within a limited space, and while not so intense as at the same pressures in the small tube, the difference in intensity did not seem sufficient to account for the difference in spectrum. In the large tube the discharge seemed more noisy and disruptive, just as though the cathode rays discharged from the walls of the smaller tube might have had some effect in facilitating the discharge. With both condenser and self-induction the large tube fluoresced very strongly, as though vigorous actions of some sort were going on at its surface.

All of these facts are suggestive, if not conclusive, and show that the effects of the walls of vacuum tubes cannot safely be neglected in the study of spectra.

It seems possible that the peculiar effects of self-induction noted by Hemsalech[2] may be accounted for in a similar way, not as a result of modified intensity of discharge or temperature,

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[1] *Wied. Ann.*, 41, 473, 1890.

[2] G. Hemsalech, *Thèse*, Paris, 1901.

but as dependent upon the time allowed for the discharge of negative electricity. Spottiswoode and Moulton showed that the time required for the discharge of "molecular streams" from the cathode was of the same order as that for the discharge of negative electricity. If these molecular streams consist of the particles which splutter from the cathode, the initial spark of a rapid oscillatory discharge must pass through air because there has been no time for sufficient metal to pass off; but by the time the second oscillation begins some metal has passed off and carries the discharge. When the oscillations are made slower by self-induction, there will be enough metal present from the beginning to carry the discharge. Why the self-induction brings out the negative-pole bands of air with some metallic electrodes is not so clear; but perhaps a difference in the time of discharge of molecular streams with different metals as compared with that of the discharge to air may account for it.

It seems likewise possible that some vacuum tube effects which have been held to suggest electrolysis may also depend upon the relative times required for negative electricity to discharge itself into different gases and metallic vapors. The spectrum of traces of hydrogen and of metallic vapors in vacuum tubes may appear stronger at the cathode simply because the discharge to them may take place more easily and more rapidly than to the gas, so that they can act as stepping-stones between the cathode and the latter. At the anode the converse may be true.

It seems obvious that this and other important questions regarding the division of the current in mixed gases, differences at the electrodes, and the effect of different forms of electric discharge can be most satisfactorily dealt with by photographing the spectrum of all parts of the tube simultaneously. An effort will be made to carry these preliminary results farther with improved methods which will allow accurate adjustment, greater dispersion, and an extension of the observations to the ultra-violet.

The conclusions suggested by this preliminary work may be summarized as follows:

1. The negative pole spectrum of nitrogen is due to cathode

rays. The intensity of the negative bands with simple discharge is dependent solely upon distance from the cathode, and is independent of changes of potential gradient in the tube.

2. The positive bands are present in the spectrum of all parts of the tube, but are of variable intensity, which seems to depend in large part upon the potential gradient.

3. The presence of the negative pole bands in the spectrum of all parts of a tube when strong discharges are used is due to the discharge of cathode rays from the walls of the tube.

4. The enhancement of the negative bands by self-induction is due to the slower rate of oscillation, permitting a more complete discharge of negative electricity, which requires more time than the positive.

UNIVERSITY OF CALIFORNIA,
March 1, 1903.

ON A NEW RELATIONSHIP BETWEEN ARC AND SPARK SPECTRA.[1]

By J. HARTMANN.

IN collaboration with Dr. Eberhard[2] I recently pointed out that in the spectrum of the arc under water the lines otherwise observed only in the spark spectrum, appear in the case of different metals—a phenomenon also previously noted by other observers with the arc burning in a hydrogen atmosphere. I have now succeeded in finding a way by which the arc spectrum can be transformed into the spark spectrum in atmospheric air also, hence without any alteration of the dielectric. I desire briefly to communicate in what follows these experiments, which give us a new insight into the processes involved in electric discharges.

My experiments were at first concerned with the spectrum of magnesium, which is of such great importance in astrophysics. As early as 1888 Liveing and Dewar[3] had pointed out that the line at λ4481, which otherwise occurs only in the spark spectrum, appears also in the arc spectrum if this is made to pass between two magnesium rods, and not between carbon poles into which the metal was introduced, as was the general practice. I had photographed the spectrum of the arc between metallic poles several times, and was surprised that I always found only faint traces of the line λ4481, while this had been obtained on the spectrograms published by Crew[4] in 1895, taken with the "rotating arc,"[5] as one of the strongest lines, and at least ten times as strong as the neighboring "arc line" λ4352. Basquin[6]

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[1] Translated from advance proofs, furnished by the author, of a paper to appear in the *Sitzungsberichte der K. Akad. der Wiss. zu Berlin.*

[2] ASTROPHYSICAL JOURNAL, 17, 229–231, 1900.

[3] *Proc. R. S.*, 44, 241, 1888.

[4] *Normal Spectrum of the Magnesium Arc.* Evanston, 1895.

[5] HENRY CREW and ROBERT TATNALL, "On a New Method for Mapping the Spectra of Metals," *Phil. Mag.* (5), 38, 379, 1894.

[6] "The Spectrum of Hydrogen Given by the Metallic Arc of Tin, Copper, Silver," etc., ASTROPHYSICAL JOURNAL, 14, 13, 1901.

also reached the conclusion that the line 4481 appears in the rotating arc, but not in the arc between stationary metallic poles in the air.

In the method of the rotating arc employed by Crew, numerous interruptions of the current occur, and we might suspect that the extra currents associated with the formation of the spark might have produced a spectrum similar to that of the spark, since the circuit contained coils of wire when the direct current from the dynamo was used. To exclude this possibility I have always used the current from a storage battery of 60 cells, and have avoided all coils of wire in the circuit, aside from a few turns of a resistance coil from which no self-induction could be feared. The observations described below were made on photographs taken with stellar spectrograph No. I of the Astrophysical Observatory.

In order first to determine whether the line at λ 4481 appears only at the instant of lighting or extinguishing the arc, or whether it appears only at definite positions in the arc, a photograph was made of the spectrum of the metallic arc when burning quietly, those two instants being excluded while the images of the electrodes were projected on the slit. The current was of about 6 ampères at a voltage of 120. This plate shows the line λ4481 to be actually present in the spectrum of the quiet metallic arc, but also that it appears principally at the electrodes, as in case of the spark discharge, while it is hardly visible at the center of the arc of about 8 mm length. But even close to the electrodes the intensity of the line was not great, certainly very much less than that of the line λ4352. If we denote with J the intensity of the spark line λ4481, that of the arc line λ4352 on the same plate being taken as unity, we may summarize the result of this plate as follows:

METALLIC ARC IN AIR 8 mm LONG, AT 120 VOLTS AND 6 AMPÈRES.

At the electrodes - - - - - - $J = 0.1$
At the center of the arc - - - - $J = 0.01$

This experiment would therefore be insufficient to explain the high intensity ($J = 10$) of the line on Crew's plate, for even if it were desired to use light only from the immediate neighborhood of the electrodes, the line at λ4481 would still appear decidedly fainter than the arc line λ4352. I then began experiments with different current strengths at a constant voltage of 120, since I suspected that the current strength might have an influence on the intensity of individual lines. I employed incandescent lamps for resistance in order to cut down the current sufficiently without introducing resistance coils.

Since the occurrence of the line in the quiet metallic arc was proven by the above-described experiment, I no longer projected the arc upon the slit and no longer excluded from the plate the instant of starting and extinguishing the arc. Hence J denotes the intensity of the line in the total light radiated by the arc. These experiments now gave the quite astonishing result that the 4481 line becomes the stronger as the current strength is lessened. Repeated photographs gave the following results:

METALLIC ARC IN AIR AT 120 VOLTS.

At 8 ampères	$J = 0.03$
6 "	0.05
3 "	0.5
0.8 "	3
0.4 "	10

These figures clearly show how the intensity of the spark line relatively to the arc line continuously increases with decreasing current strength; and indeed so regularly that it would be easy, for instance, to specify the current strength at which the two lines would appear of equal intensity; this would occur at about 2 ampères.

In view of the result of these experiments it would be difficult to maintain the assertion that the line λ4481 is an evidence of a very high temperature of the metallic vapors, for the development of heat is certainly not greater in the arc at 0.4 ampères than at 8 ampères with the same voltage. With the latter current strength the electrodes were so greatly heated as readily to melt, and the vaporization of the metal was so great that the poles could be separated by more than 10 mm; while at 0.4 ampères the electrodes were entirely cool and the arc could not be lengthened beyond 0.5 mm at most, and then it burned for hardly more than a second, and had to be very frequently started up.

It might now perhaps be asserted that close to the electrodes the temperature of the vapor is so much higher than at other parts of the arc that, as a direct consequence of the small separation of the poles required by the low current, the *average* temperature of the whole arc was higher in the latter case than if the arc had a stronger current and greater separation of the poles, and could perhaps cool off more near its center. But were this assumption correct, then in the first-described arrangement of the experiment with the projection of the portion of the arc close to the pole, the intensity of λ4481 should have been correspondingly high—in fact, much higher than the intensity of the arc line λ4352. This, however, was not most remotely the case, since the intensity in that case also was only 0.1. There remains, therefore, nothing else to assume than that the conditions for the development of those molecular vibrations to which the line λ4481 corresponds were much more favorable in the small arc in spite of its lower, or at least certainly not higher, temperature than in the larger arc.

It cannot at present yet be stated with certainty what constitutes these "conditions," but we might hope to find an explanation of the observed phenomenon in the following two facts. As already stated, the small arc went out very frequently, and had to be started several hundred times during the exposure, which lasted for about half an hour on account of the small brightness of the point of light, so that only a comparatively short time of quiet burning followed each rekindling. The observed changes of intensity could be reasonably explained, if we assume that at the moment of kindling or of extinction another spectrum occurred in which the line λ4481 was strongly predominant. The correctness of this explanation could be determined by successive exposures of the arc with a rotating mirror or on moving films, which have recently been carried out in a very complete manner, for instance, by Crew and Baker.[1]

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[1] "On the Thermal Development of the Spark Spectrum of Carbon," ASTROPHYSICAL JOURNAL, **16**, 61, 1902.

Should the explanation prove to be correct, it is to be noted that this introductory spark should by no means be confused with the commonly observed induction spark; with the precautions that I have described it can possess no elevated tension and temperature. We should rather conclude only that at the moment of the first passage of the electricity from one electrode to the other particles of metal are torn off which even at low temperature execute vibrations corresponding to the line λ4481.

The second fact which could be adduced in explaining the phenomena I have observed would make the line λ4481 appear, not as a high-temperature line, but even as one of low temperature, if such a designation were indeed at all permissible. According to an observation by Schenck,[1] which I was also able to confirm, the intensity of the line 4481 decreases in the *spark spectrum* if the electrodes are heated to the point of melting, so that the resistance in the spark gap is diminished by the active vaporization of the metal. I found further in another experiment that the intensity of this line decreases if the resistance in the dielectric is reduced by exhaustion. If we transfer this to the arc spectrum, we shall obtain a very good explanation of the phenomena in question. We may assume, according to Schenck's investigations, that the line λ4481 results from the vibrations of particles highly charged with electricity, and therefore it can appear only of reduced intensity, if at all, if such a charge is in any way prevented. Now, as soon as the electrodes are heated by the stronger current there occurs a vigorous vaporizing of the metal, the conductivity in the arc becomes greater, and the separate particles take on only very slight charges, so that the vibrations corresponding to the line λ4481 must always become weaker with increasing current strength.

As I have already remarked, the magnesium electrodes very soon melted when only moderate currents were used, and thus they immediately set a limit to further heating and vaporization. When using metallic electrodes the experimenter is therefore compelled by the purely incidental process of melting to main-

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[1] "Some Properties of the Electric Spark and its Spectrum," ASTROPHYSICAL JOURNAL, 14, 116, 1901.

tain the poles in a cool condition in some way, whether by artificial cooling, by the employment of a very small current, by the frequent interruption of the current, or by the continual introduction of new and cold parts of the metal into the arc. Crew employed the latter process in his rotating arc, and in consequence obtained so powerful a 4481 line, as above stated. The vaporization was similarly very slight in the small arc with 0.4 ampères, and the line accordingly was very strong, becoming more and more faint with the increasing vaporization of the electrodes.

The absence of this line from the carbon arc can be very simply explained in this way. If magnesium is introduced into the arc burning between carbon poles, the above mentioned limit is no longer set for the greater heating and vaporization of the metal, and the arc becomes a very good conductor, as might already be inferred from its greater length, whereby, in accordance with what has been said, the disappearance of the arc line is occasioned.

The ingenious experiments of Basquin[1] who simultaneously caused the arc and the spark to pass between the same electrodes, are also in full agreement with the view here developed. When a second spark gap was introduced into the circuit of the spark discharge, there appeared in the arc simultaneously the arc and the spark lines. If, however, the second spark gap was made very short, the spark lines disappeared completely in the arc, although the spark discharges passed through the arc as before. If the arc current was now interrupted, there was a duration of about a second before the spark began to pass in the ordinary noisy manner, and then the spark spectrum also first appeared. This experiment proved, first, that in the condition of the vapors prevailing in the electric arc those molecular vibrations are also possible to which the spark lines correspond; and second, that these vapors, even up to a second after the extinction of the arc, conduct so well that a high-tension current can pass between the electrodes without forming sparks, therefore without producing the spark lines.

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[1] *Loc. cit.*, p. 15.

I would also revert here to the experiments which I made, in common with Dr. Eberhard,[1] using zinc electrodes. We succeeded, in the first place, in showing that the spark spectrum of this metal approaches the arc spectrum on artificial heating and vaporization of the zinc electrodes, in a manner analogous to the process observed by Schenck. But *per contra*, we did *not* succeed at that time with the reverse experiment, namely, of transforming the arc spectrum into the spark spectrum by cooling the electrodes with liquid air. This failure may, however, be simply explained if a very high temperature still prevails at the points of the greatly cooled electrodes; we might infer that this was the case from the fact that the arc could be drawn out to a length of several millimeters without going out. It is possible that a photograph would have shown a slight alteration in the relative intensity of the arc and spark lines, but on account of its difficulty this experiment was not made. But we did succeed in obtaining very distinctly the two zinc spark lines at λ4912 and λ4925 on reducing the current to 0.5 ampères and by using very large poles which conducted the heat well, although we had found hardly a trace of these lines in the arc with a current of about 6 ampères.

I have obtained a further confirmation of my observation on magnesium in the spectrum of bismuth. The very strong spark line at λ4260, which does not appear in the carbon arc, appears in the arc between metallic poles only slightly fainter than the neighboring arc lines at λ4254 with 6 ampères current; but at 0.3 ampères it still appears very distinctly, while the arc line has wholly disappeared.

With lead electrodes in the arc I succeeded even at 6 ampères in obtaining the two principal spark lines, at λ4245 and λ4387, although they do not appear at all in the carbon arc. In order to test still further whether the small amount of vapor between the electrodes is in fact a sufficient cause for the appearance of spark lines in the arc, I made the experiment with this metal in such a manner that the one electrode consisted of melted lead, heated to active incandescence and vaporization. When the

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[1] *Loc. cit.*, p. 41.

same current of six ampères was passed across from this vaporizing mass of metal to a cold lead pole there no longer appeared any trace of the two spark lines in the arc spectrum. This observation accordingly also furnished a proof of the correctness of the view expressed above.

Since we might be inclined to assume that a high voltage is necessary for the production of the vibrations corresponding to the spark lines, which is indeed always present in the ordinary spark discharges, I made the further attempt of also bringing out the spark lines, which are under ordinary conditions lacking in the arc, merely by diminishing the tension while the current strength remained constant. This experiment was also completely successful. For this I again used magnesium poles, and employed the current of 20 volts and 4 ampères from ten storage cells. The development of heat was so slight that there was no longer any appreciable vaporization of the metal, whence the formation of an actual arc was excluded. The very small introductory spark, certainly hardly 0.1 mm long, which appeared every time the poles were separated from electrical contact, showed the line 4481 decidedly stronger than did the longer arc, in spite of the fact that it surely had no higher temperature than the arc with equal current strength and sixfold greater voltage. My photograph gave

at 20 volts and 4 ampères - - - $J = 10$

while from the figures above we get

at 120 volts and 4 ampères - - - $J = 0.3$

Although the consumption of energy is in this case reduced to one-sixth, the relative intensity of the spark line nevertheless has risen about thirtyfold.

All of my observations which I have here described, as well as the results of numerous other observers, of which I have mentioned only a few above, indicate that the spark lines do not correspond to a thermal radiation but rather to electroluminescence. This idea is not new, but was expressed in the following very precise manner in 1888 by Liveing and Dewar,[1] when they discovered the occurrence of the λ4481 line in the

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[1] *Proc. R. S.*, **44**, 241–242, 1888.

arc spectrum: "The observations, however, render doubtful the correctness of the received opinion that the temperature of the spark discharge is much higher than that of the arc. Heat, however, is not the only form of energy which may give rise to vibrations, and it is probable that the energy of the electric discharge as well as that due to chemical change, may directly impart to the matter affected vibrations which are more intense than the temperature alone would produce."

This clearly expressed view unfortunately received too little attention at the time, and in later years hypotheses have been founded on the wholly unproven assumption, rendered dubious by the above remark by Liveing and Dewar, that the spectrum of an incandescent gas is a function of only the *one* variable, "temperature," which hypotheses should render possible a direct conclusion as to the temperature of the luminous gas from the occurrence of individual lines. This would have been not without significance, especially for astrophysical research, although there exist other methods, free from objection, for determining the temperature of celestial bodies; but, as I have shown, such a conclusion is not permissible, at least in so far as the magnesium lines λ4481 and λ4352 are in question, since so far a proof is entirely lacking that the line λ4481 always corresponds to a higher *temperature* than the line λ4352. We should be inclined from my experiments described above to reach the contrary conclusion, but such a conclusion is also unpermissible, since, as is confirmed by all previous observations, the production of the spark lines probably is not related to the temperature. I do not regard it to be impossible that those molecular vibrations which cause the occurrence of the spark lines, whose excitation has hitherto been solely possible by the use of electric discharges, may occur exclusively by the introduction of energy in the form of heat; but for the correctness of any such assumption no laboratory demonstration can yet be adduced.

In view of what has been said, it may well be difficult further to maintain the hypothesis advanced by Scheiner[1] in 1894.

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[1] "Die Temperatur an der Oberfläche der Fixsterne und der Sonne, verglichen mit derjenigen irdischer Wärmequellen," *Sitzungsberichte der k. Akad. der Wiss. zu Berlin*, 1894, p. 257.

Inasmuch as the line λ4481 appears very strong in the spectra of numerous stars belonging to Vogel's first type, while λ4352 is very faint or not present, Scheiner reached the conclusion that on these stars the temperature of the absorbing layer was approximately that of the electric spark, while the temperature of the stars of the second and third type, in whose spectrum the line λ4352 more strongly occurs, the temperature approximated more closely that of the arc. The above demonstration that the intensity ratio of the two lines denoted by J by no means increases with rising temperature, indeed probably stands in no direct relation to the temperature, causes these conclusions to lose their foundation as well as their force.

But there is still a further circumstance to be considered. As has been shown by the observations of Crew,[1] Basquin,[2] and Porter,[3] as well as by the above-mentioned investigation by Eberhard and myself, the dielectric has a great influence on the spectrum of electrical discharges. Now since all stars of the first spectral type are characterized by a great preponderance of hydrogen in their atmospheres, it would seem that only observations which have been made in an atmosphere of hydrogen should be adduced in interpreting the spectra of those stars. It was already known from the publications of the first-named observers that the hydrogen atmosphere so favored the appearance of the line 4481 that it also came out very strong in the arc, and I therefore suspected that my experiments in a hydrogen atmosphere discussed above would furnish still larger values of J. This expectation was most fully confirmed, for a photograph of the arc burning in a hydrogen atmosphere at 120 volts and 0.3 ampères showed *no trace of the arc line*, while the line 4481 came out perfectly sharp and as the strongest line of the whole spectrum; in addition to this line the spectrum further contained only the three lines λ3830, λ3832, and λ3838, and

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[1] "On the Arc Spectra of Some Metals, as Influenced by an Atmosphere of Hydrogen," ASTROPHYSICAL JOURNAL, 12, 167, 1900.

[2] *Loc. cit.*, p. 1.

[3] "The Influence of Atmospheres of Nitrogen and Hydrogen on the Arc Spectra of Iron, Zinc, Magnesium, and Tin, Compared with the Influence of an Atmosphere of Ammonia," ASTROPHYSICAL JOURNAL, 15, 274, 1902.

very faintly the *b* group. Accordingly the strength of the 4481 line and the absence of the arc lines of magnesium in stellar spectra of the first type can no longer be regarded as striking. It would seem to be more important to give some attention to the occurrence of the two above-mentioned magnesium triplets. These are the most permanent lines in the portion of spectrum I have investigated, occurring with every form of luminosity, even in the spectrum of burning magnesium, and we may well assume that the corresponding molecular vibrations are of a purely thermal origin. Nevertheless, they do not occur in many star spectra which contain a strong 4481 line, as Keeler[1] has already remarked of the *b* group.

The last-mentioned spectrum photograph shows a further peculiar appearance which I should not leave unmentioned. While those two triplets and the line 4481 are all that remain of the whole magnesium spectrum, there further appear on the plate as impurities of the metal, the three calcium lines λ3934, λ3969, and λ4227, as well as the lead line λ4058—all of them lines which, like the triplets, are easily reversible and make their appearance at low temperatures. Just as the method of oscillating discharges first employed by Schuster and Hemsalech, which permits a gradual transition from the spark spectrum to the arc spectrum, so also the method of the "small arc" described here, which represents the inverse transition from the arc to the spark spectrum, should be suitable for furthering the discovery of related groups of spectral lines, and hence for the study of the processes of luminosity.

ASTROPHYSICAL OBSERVATORY,
Potsdam, February 26, 1903.

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[1] "The Magnesium Spectrum as an Index to the Temperature of the Stars." *Astronomy and Astro-Physics*, 13, 660, 1894.

DISCUSSION OF A QUESTIONABLE TYPE OF TEMPORARY STARS.

By J. G. HAGEN, S. J.

IT is understood that by a "temporary star" is meant a star which has been seen to vary in brightness a single time, although this variation may have extended over months or years, and may have been composed of fluctuations of various amplitudes. If two or more variations of this kind have been observed, the star is usually called a periodic variable, regular or irregular.

When the outburst of a temporary star was so short in duration that it was seen by one observer only, without independent confirmation by another, the record has generally been received with suspicion and accepted with explicit reserve. This is the case with two stars that have found a place in the catalogues of variable stars. There are three more instances of an earlier date, one of which has never been published. A simultaneous inspection of these five cases and of the authorities on which they rest will probably remove all reasonable doubt as to the existence of short variations of this kind. The astrographic charts, which give three successive exposures to the stars, may reveal some more variations of this character by abnormal intensities in the points of the small stellar triangles.

The five temporary variations of short duration will be related in the inverse order of time, beginning with the most recent. They can very conveniently be put in three groups.

I. TWO KNOWN TEMPORARY STARS OF SHORT VARIATION.

1. The star *U Scorpii* is No. 73 in *Schönfeld* I, No. 87 in *Sch.* II, and No. 5860 in *Chandler* I-II. When Pogson observed its variation in 1863, he was government astronomer in Madras, and had a ten years' experience on variable star work. He saw the star decrease from 9th mag. to invisibility in twelve days. The star has never been recognized by anyone else, but is called by Pogson a well-assured, rapidly changing star. The chance for

a second observer to see the variation was probably confined to one or two days. When the star was below mag. 10 it would have been very difficult to identify it without a chart.

2. The other star is *T Bootis*, No. 58 in *Sch.* I, No. 70 in *Sch.* II, and No. 5097 in *Ch.* It is almost of exactly the same character as the former, and was observed in England only three years previously, in 1860, by Pogson's brother-in-law, J. Baxendell. On April 9 it was of magnitude 9¾, on April 11 of mag. 10, on April 20 of mag. 12.8, and on April 23 it was invisible (in Baxendell's own scale). The variation was observed during twelve days, but the chance for independent confirmation could hardly have extended over more than two days.

II. TWO INSTANTANEOUS VARIATIONS OF LIGHT.

1. An instantaneous fluctuation of light was observed by Pogson in the star *U Geminorum* on March 26, 1856, while he was preparing a chart for this variable. Pogson was then assistant astronomer at the Radcliffe Observatory in Oxford, where he had commenced working on his intended atlas of variable stars three years previously. His observation has lately been published in the *Astronomical Journal* (**22**, 127, 1902), from which we quote what is essential: "The variable subject to strange fluctuations at intervals of 6 to 15 seconds. . . . . when the adjacent stars were quite steady. At times it surpassed the star 8.9, at others it quite vanished. . . . . Watched it for half an hour, with powers 54, 65 and 95 on the equatorial." The comparison star 8.9 is probably No. 5 in the *Atlas Stellarum Variabilium* (Series II, 2815). The range of these fluctuations seem to have been the same as that of the periodic changes of this variable.

2. A similar fluctuation of light was observed by Heis in the star *ζ Lyrae* on September 26, 1850. Heis observed the variable star *β Lyrae* from 1841 to 1868, and used as comparison stars, among others, ε and *ζ Lyrae*. Each of these has the magnitude 4½, but appears double to the naked eye on very clear nights. Heis found the relative brightness of these two comparison stars slightly changeable. On the date mentioned the observing book (which will soon appear in print) has the following note: *ζ Lyrae*

became for a *moment very bright*, and then again faint" ("ζ *Lyrae* wurde einen *Moment sehr hell* und hierauf wieder dunkel").

The star probably did not reach the brightness of the neighboring first-magnitude star *α Lyrae*, else Heis would hardly have omitted the comparison. The time of the fluctuation must have been too short to be measured, because Heis was in the habit of recording the time in whatever he observed.

The short note deserves the more confidence, as Heis had been familiar with this comparison star for nine years; further, as his eyes saw the stars as distinct points without false rays (see E. Heis, *De Magnitudine relativa*, etc. Monasterii, 1852, page 4), and finally as his observations of variable stars show a rare precision in estimating steps.

III. AN OLD OBSERVATION OF CHRISTOPH SCHEINER, S.J., IN 1612.

This observation is described by Scheiner in his second letter to Welser, dated April 14, 1612, and printed in his book: *De Maculis solaribus*, etc. Augustae Vindelicorum, 1612. As this book is rare, Winnecke republished the Latin text in the *V.J.S.* (**13**, 283–288, 1878).

1. What Scheiner *observed* may be summarized as follows: He gives nine drawings of the field of view in his telescope, which he calls the best he ever saw for observing *Jupiter's* satellites. They were made when the sky was very clear and without moonlight. They give the relative positions of the planet *Jupiter* and its satellites, on March 29, 30, 31; April 1, 3, 5, 6, 7, 8. In the same field a star denoted by the letter E is drawn, about 6′ south of the planet. Scheiner's argument that this star had a motion of its own is evidently not conclusive. It is based on eye-estimates only of its motion relative to the planet, which became stationary a few days later, about April 10. Scheiner was prejudiced on this point by the hope of discovering a fifth satellite of *Jupiter*.

What he says about the light of this star is of more importance. The first drawing, on March 29, shows nothing of the star in question. On March 30 Scheiner saw it for the first time (*primus illius contuitus mihi obtigit*), and, as is usual with temporary stars, at once very bright and large (*lucentissimam et maximam*), like any of *Jupiter's* satellites (*quanta . . . . hactenus quaevis conspecta est stella Jovialis*), and, as he adds a little later, much brighter and larger than the fainter satellites, which he describes as much inferior in light and size (*lucis et corporis multo quam potiebatur stella E minoris*). During the following days it fell below the fainter satellites, until, on April 8, it was seen with great difficulty (*ægerrime*) in a very clear sky. After that date it was never seen again, although carefully looked for under favorable conditions. Scheiner had several smaller telescopes with which the star was seen at its greatest brilliancy. He also showed the star to his friends.

2. *The identification* of this star was made by Winnecke.[1] With the help of Küstner he found from Leverrier's tables of the Sun and *Jupiter* that the position of Scheiner's star was identical with the place of *B.D.* + $15^\circ\!.2083$, $8^m\!.5$, within the residuals 0^s, $1'\!.4$. This star is not a periodic variable. It has been constantly recorded as of magnitude 7–8 or 8 or 8.5, by Lalande (1796), Weisse (1825), Struve (1826), Preuss (1833), in the *B.D.* and the *H.P.* Winnecke himself watched it for seventeen years. Among the thirteen observations in the *H.P.* (Vol. 24, page 220) there is one large residual from the mean magnitude 8.0, amounting to +2.4, which would make the star $10^m\!.4$; yet the series 991, in which this residual occurs, has the accompanying remark: "thin clouds noticed in various parts of the sky" Vol. 23, Part I, page 39). Clouds will explain any positive residual, and also any negative residual, if the pole star, which served as comparison star for the meridian photometer, was covered by them.

3. For the *range* of the light variations we can deduce from Scheiner's description an approximate upper limit. The literature on the photometry of *Jupiter's* satellites is put together in Dr. Müller's *Photometrie der Gestirne*, pp. 385–393. The mean

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[1] Winnecke makes no reference to the possibility that Scheiner's star might have been a planet, stationary near *Jupiter*. *Uranus* and *Vesta* reach the brightness of *Jupiter's* satellites, but would hardly show variations as those described. We leave this question open and base our further discussion on Winnecke's opinion that the star in question was a fixed star.

results of Engelmann's, Pickering's, and Spitta's photometric measures for the faintest and brightest satellites are the following: satellite IV: $6^{\mathrm{m}}.5$, and satellite III: $5^{\mathrm{m}}.5$, the other two ranging between. These figures hold for "mean opposition," *i. e.*, for the opposition of Earth and *Jupiter* at their mean distances, and for the mean albedo or reflecting power of the satellites. The reduction to quadrature, at which Scheiner observed, would diminish these magnitudes only $0^{\mathrm{m}}.1$ or $0^{\mathrm{m}}.2$, as may be concluded from Engelmann's reductions of Dr. Auwers' visual observations (*Helligkeitsverhältnisse der Jupiterstrabanten*, Leipzig, 1871, page 67), while the varying albedo may change these figures by $\pm 0^{\mathrm{m}}.5$ (Engelmann, *loc. cit.*, page 69).

If we now remember that Scheiner calls his star E as bright as any satellite, and much brighter than the fainter satellites, we are safe in saying that his star had reached the sixth magnitude. In ten days it faded away to invisibility. This limit, in a telescope which was considered good and showed the fainter satellites well, should be at least as low as eighth magnitude, the normal brightness of star E. What the lower limit of the fluctuation actually was cannot be gathered from the data on hand.

Winnecke was familiar with Scheiner's writings and judges him as "thoroughly trustworthy in communicating what he had seen."

In conclusion these five instances seem to show that short variations in the light of stars, although noticed by only one observer, cannot be rejected when assured by good authority. Should Heis' remark on ζ *Lyrae* be considered too short or too casual to inspire full confidence, it seems that Scheiner's star in the constellation *Leo* has as much claim for enlistment among the temporary stars as *U Scorpii* and *T Bootis*. The star *U Geminorum* will always remain among the periodic stars, but its extraordinary fluctuation in 1856 should be borne in mind.

GEORGETOWN COLLEGE OBSERVATORY,
February 1903.

ON THE EFFECT OF CIRCUIT CONDITIONS UPON THE WAVE-LENGTHS OF SPARK LINES.

By NORTON A. KENT.

IN the summer of 1901 Professor Charles E. St. John, of Oberlin college, and the writer of this article, at the suggestion of Professor Hale, undertook to verify certain results obtained by Haschek[1] in regard to the relative position of the arc and spark lines of titanium.

Haschek had found that in some cases the displacement of spark lines toward the red from the position of the corresponding arc lines exceeded 0.1 tenth-meter, *e.g.*, 0.13 for *Ti* λ 3900.68. These were unusually large displacements.

After continuing the investigation alone for a short time[2] the writer was obliged to defer its completion to take part in a more important study (that of the spectrum of the electric discharge under liquids), and only recently has it been possible to return to the former subject.

APPARATUS USED.

The apparatus used was, in its general features, the same as that employed in the investigation of the spectrum of the electric discharge in liquids, and a description of the same will appear in the *Publications of the Yerkes Observatory* soon to be issued. For the present purpose a brief description will suffice.

A 5-horse-power motor drove a 3.3 kilowatt alternator (125 cycles per second, potential 110 volts, current 30 ampères), which fed a 1 kilowatt Lakon transformer. An adjustable condenser gave a capacity of from 0.0066 to 0.0560 microfarads. The arc and spark apparatus were set upon the circumference of a circle at the center of which was a plane silver-on-glass mirror, capable of being rotated about a vertical axis. The light could then be thrown from either piece of apparatus to a concave

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[1] ASTROPHYSICAL JOURNAL, 14, 181, 1901.

[2] *Ibid.*, 14, 201, 1901.

mirror fitted with slow-motion screws which gave motions about horizontal and vertical diameters. From this latter mirror the light passed to the slit of the spectroscope — Rowland mount: radius of curvature of grating 10 feet; 15,000 lines per inch. The first spectrum alone was used; the dispersion was 5.63 t. m. per mm. The arc (direct current) was so arranged that after contact the carbons could be moved apart to a stop; this gave an arc of constant length. A current of 18 ampères was used in all cases. Before every exposure a small piece of metal, several milligrams in weight, was placed in a shallow hole in the lower carbon which formed the positive pole of the arc. These precautions were taken to avoid any possible change in the position or intensity of the standard lines of the comparison spectrum. Suitable shutters made possible the method of double exposure of the comparison spectrum. The arc was exposed for ½ second; then the spark for various lengths of time; then the arc again for ½ second, this third exposure being superimposed upon the first.

It will be noticed that the mirror method — suggested by Professor Hale — furnishes an easy means of avoiding the possibility of any false shifts due to unequal illumination of the grating. The short time of exposure employed for the arc might introduce such shifts unless all parts of the beam were exposed an equal time. For this reason, and also to facilitate obtaining arc spectra of the same intensity upon every plate, the following arrangement was used: a camera shutter, set less than an inch in front of the slit and operated pneumatically by a long tube and bulb, was fitted with a horizontal rectangular window. This window was so arranged that when the shutter was set the slit of the spectroscope was covered. When the bulb was pressed the beam was disengaged from the left side, and subsequently covered from the left side. Then the shutter automatically returned to its former position, repeating the above process in the reverse direction. Thus each of the four sets of exposures of ¼ second duration was complete in itself. As previously stated, the shutter was close to the slit, and on this account as well it seemed improbable that any error due to unequal illumination of the grating would enter. The device worked most satisfactorily. The arc was thrown upon the shutter by setting the plane mirror properly and making final adjustments (always small) with the concave mirror. During this procedure the image was viewed with a telescope. Then the bulb was pressed and the exposure made.

The spark terminals were formed of pieces of titanium carbide or "cast titanium," 85 per cent. *Ti* and 15 per cent. carbon, purchased of Eimer & Amend, of New York. The shape of the terminals was not regular; but rough edges were presented to each other and the pieces shifted often to obtain new edges. It is to be regretted that time did not permit greater care in this respect, for it is well known that the form of the surface alters the potential of discharge, and this *may* affect the position of the line. Still it may be stated that the results show no errors which can be traced directly to this cause.

The displacements were measured with a Zeiss comparator of double microscope pattern, under a magnification of about eight diameters. Double parallel wires were found to give most accordant results. The plates were placed violet left and four settings were made on the comparison, or arc spectrum with three on the internal or spark spectrum; then the same set of measurements was repeated with the plate placed violet right.

RESULTS.

The results of the investigation are given in Tables I to IV. Table I shows the agreement between different plates, those in each group of two or three plates being taken under similar conditions as far as known, and the groups differing among themselves by reason of change of spark-length, capacity, etc. The average deviation from the mean of the measurements made upon the individual plates of the different groups is 0.005 tenth-meter, and the average deviation from the mean of the measurements of the four lines on the same plate (chosen at random) is under 0.003 tenth-meter.

Table II covers the results of six short series, upon which series the following brief remarks may be made:

A. *Changing the length of the primary or main gap*[1] apparently causes a change in the position of the spark line. The spark was vertical and its length was varied from 1 to 20 mm. The slit of the spectroscope was cut down to 6 mm; the concave mirror was so mounted that it gave an image 2.4 times as large as the source. In the three cases, then, the images were 2.4, 24, and 42 mm in length. Therefore the whole image of only the shortest spark fell upon the slit. With the 10 and 20 mm sparks the central 2.5 mm were used. This point will be discussed later. In Plates 11 and 12 a strong air-current was directed upon the spark by an electric fan—this to produce greater disruptiveness in the discharge. It may appear that the true series should be composed of Plates 3 and 4, 13 and 14, and 1 and 2; for in none of these was the fan used. But it may be well to remark that in 3 and 4, and 1 and 2, the spark was highly disruptive, in 13 and 14 it was not. (At this seemingly critical spark length it so much resembled the uncondensed spark that the exposure time had to be increased to 4 minutes, from 15 seconds in 1 and 2.) Therefore 11 and 12 may well lay claim to the right of being substituted for 13 and 14. *Probably* the fan will increase the displacement in all cases in which the spark is not inherently disruptive.

B. The work upon the spectrum of the spark under liquids (carried on in conjunction with Professor Hale), in which an *auxiliary air gap* was placed in the discharge circuit of the condenser in series with the liquid gap to produce sufficient disruption of discharge, at once suggested the trial of the effect of a second air gap in this case also. The results in the two cases, spark under water and spark in air, are identical as far as displacement is concerned: the introduction, or an increase in length, of the secondary gap produces an increase in displacement. The fan forced a current of air against both gaps.

C. *Increase of capacity* over the range employed seems to produce a small increase in displacement. For values of plates of the condenser in meters and microfarads see Table III.

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[1] The difference between primary and secondary gaps will be made evident in section B.

D. *Introduction of self-induction*, even as small an amount as 0.000426 henries, into the discharge circuit of the condenser produces a great change: under such conditions the spark lines are more nearly coincident with the arc lines.

E. *Introduction of impedance*, of considerable but unknown amount[1] into the primary circuit of the transformer, has some influence on the position of the lines.

F. *Introduction of resistance* into the exciting circuit of the alternator, in addition to that of the field coils themselves, causes a decrease in displacement. Whether this change will always be in this direction—increased resistance, decreased displacement—is an open question. For certain reasons, which cannot be discussed here, but will be made evident in the *Publications of the Yerkes Observatory*, the writer is led to believe that under some conditions an increase of resistance may cause an increased displacement.

The effects of five[2] of the six sets of changes have their exact parallel in the water spark, and, indeed, the attempt to obtain such effects was suggested by the results obtained in that investigation. This collateral evidence goes far to compensate for the meagerness of data here presented. Moreover, in the spark in air at high pressure (210 pounds), introduction of self-induction decreased the displacement.[3]

It was stated above that in the primary spark-gap series only a 2.5 mm central section of the longer gaps was used. It seemed advisable to study further the 20 mm spark. Therefore the terminals were turned into a horizontal position, and a series of plates taken as shown in Table IV, to which the last portion (G) of Table I is preliminary.

The difference between the displacements given by plates 34 and 35, also by 36 and 37, Table I, is well accounted for by the fact that it was difficult to expose identically the same portions of

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[1] Impedance coil: seven sections connected in parallel, each of 150 turns of No. 16 B. & S. copper wire; internal diameter of coil, 6.3 cm; external diameter, 9.4 cm; total length of coil, 17 cm; soft iron wire core; closed magnetic circuit.

[2] In the water-spark investigation the effect of impedance was not tried.

[3] ASTROPHYSICAL JOURNAL, 17, 157, 1903.

the spark. It is perfectly evident, however, that a large difference exists between the displacement given by that part of the spark which is near the terminals and that which lies between them. From plates 36, 37, 38, and 39 it appears that there is little difference between the positions of lines given by the central portions of either long or short gaps. But no special stress should be put upon this point, because of the difficulty of placing upon the slit the central portions of either long or short gaps.

Attention should be called to the fact that plates 15, 16, and 28 do not give results which are in absolute accord with the primary spark-gap series. Nor do 36 and 37 agree well with 3 and 4. In the writer's opinion, this should not count against an acceptance of the results as accurate and of the effects as true, because (1) the plates cited were not taken upon the same day nor upon succeeding days (it is possible that a change in atmospheric conditions alters the positions of the lines); and (2) the shape of the terminals may not have been the same.

GENERAL DISCUSSION OF RESULTS.

Such large displacements as Haschek gives have not presented themselves. He used a capacity of 625 meters or 0.0694 microfarads. The maximum capacity here employed was 504 meters or 0.0560 microfarads. By referring to Mohler's table, given in his article on "Pressure in the Spark,"[1] it will be seen

TABLE I.

Relative positions of spark and arc lines observed under various modifications of the conditions of the spark circuit.

Displacement of spark lines toward red from position of arc lines given in tenth-meters. M = mean displacement.

A. EFFECT OF CHANGE IN LENGTH OF PRIMARY SPARK-GAP.

Line	Displacements for Separate Plates, with Means											
	3	4	M	13	14	M	11	12	M	1	2	M
3900.68	+.003	+.004	+.004	+.012	+.021	+.017	+.011	+.012	+.012	+.030	+.039	+.034
04.95	−.002	−.006	−.004	−.001	−.005	−.003	......	+.010	+.010	+.011	+.034	+.022
13.58	+.009	−.001	+.004	+.011	+.009	+.010	+.007	+.013	+.010	+.032	+.044	+.038
98.77	+.003	−.011	−.004	−.009	−.018	−.014	......	+.007	+.007	+.015	+.033	+.024

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[1] ASTROPHYSICAL JOURNAL, 10, 204, 1899.

TABLE I.—*Continued.*

B. EFFECT OF CHANGE IN LENGTH OF SECONDARY SPARK GAP.

Line	Displacements for Separate Plates, with Means									
	15	16	28	M	17	19	M	20	21	M
3900.68	+.010	+.014	+.017	+.014	+.028	+.026	+.027	+.044	+.037	+.041
04.95	−.010	−.012	+.003	−.006	−.003	−.005	−.004	+.019	+.027	+.023
13.58	+.007	+.007	+.018	+.011	+.025	+.037	+.031	+.041	+.043	+.042
98.77	−.007	−.012	+.010	−.003	......	+.009	+.009	+.023	+.027	+.025

C. EFFECT OF CHANGE OF CAPACITY.

Line	Displacements for Separate Plates, with Means												
	1	2	M	9	10	M	7	8	M.	4a	5	6	M
3900.68	+.030	+.039	+.034	+.030	+.042	+.036	+.040	+.041	+.040	+.050	+.043	+.036	+.043
04.95	+.011	+.034	+.022	......	......	......	......	......	......	+.038	+.029	+.031	+.027
13.58	+.032	+.044	+.038	+.034	+.043	+.038	+.034	+.049	+.042	+.054	+.040	+.030	+.041
98.77	+.015	+.033	+.024	......	......	......	......	......	......	......	+.034	+.025	+.030

D. EFFECT OF INTRODUCTION OF SELF-INDUCTION.

E. EFFECT OF INTRODUCTION OF IMPEDANCE.

Line	Displacements for Separate Plates, with Means												
	23	29	M	4a	5	6	M	26	27	M	1	2	M
3900.68	+.008	+.012	+.010	+.050	+.043	+.036	+.043	+.036	+.025	+.031	+.030	+.039	+.034
04.95	−.010	+.003	−.004	+.038	+.022	+.031	+.027	+.008	+.005	+.007	+.011	+.034	+.022
13.58	−.010	+.014	+.002	+.054	+.040	+.030	+.041	+.026	+.018	+.022	+.032	+.044	+.038
98.77	−.002	+.001	−.002	......	+.034	+.025	+.030	−.001	−.001	−.001	+.015	+.033	+.024

F. EFFECT OF CHANGE OF RESISTANCE IN FIELD CIRCUIT OF ALTERNATOR.

Line	Displacements for Separate Plates, with Means					
	24	25	M	1	2	M
3900.68	+.027	+.031	+.029	+.030	+.039	+.034
04.95	+.000	−.002	−.001	+.011	+.034	+.022
13.58	+.008	+.025	+.017	+.032	+.044	+.038
98.77	−.004	+.010	+.003	+.015	+.033	+.024

G. EFFECT OF USING DIFFERENT PARTS OF SPARK, AND SPARKS OF DIFFERENT LENGTH, AS SOURCES OF LIGHT.

Line	Displacements for Separate Plates, with Means								
	34	35	M	36	37	M	38	39	M
3900.68	......	+.058	+.058	+.026	+.019	+.023	+.029	+.022	+.026
04.95	+.017	+.023	+.020	+.021	+.007	+.014	......	......	......
13.58	+.039	+.051	+.045	+.032	+.011	+.022	+.024	+.018	+.021
98.77	+.010	+.029	+.020	+.011	−.006	+.002	+.011	......	+.011

TABLE II.

VERTICAL SPARK.

Mean displacements taken from Table I. Results of six series of plates in which length of primary gap, length of secondary gap, capacity, etc., are severally the variables. Displacement of spark lines toward red in tenth-meters: positive unless otherwise indicated.

Conditions	Plate numbers		3, 4	13, 14	11, 12	1, 2	15,16,28	17, 19	20, 21	1, 2	9, 10	7, 8	4a,5,6	23, 29	4a,5,6	26, 27	1, 2	24, 25	1, 2
	Date of exposure		Dec. 29	Dec. 31	Dec. 31	Dec. 29	Jan. 3, 5	Jan. 3	Jan. 3	Dec. 29	Dec. 30	Dec. 30	Dec. 30	Jan. 5	Dec. 30	Jan. 5	Dec. 29	Jan. 5	Dec. 29
	Length of primary spark gap in mm.		20	10	10	1	5	5	5	1	1	1	1	1	1	1	1	1	1
	Length of secondary spark gap in mm.		0	0	0	0	0	10	20	0	0	0	0	0	0	0	0	0	0
	Capacity in plates of condenser		9	9	9	9	9	9	9	9	19	38	77	77	77	9	9	9	9
	Self induction in henries		0	0	0	0	0	0	0	0	0	0	0	0.000426	0	0	0	0	0
	Impedance in primary transformer circuit		0	0	0	0	0	0	0	0	0	0	0	0	0	x[4]	0	0	0
	Field circuit resistance in ohms		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	75	0
	Fan running		No	No	Yes	No	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No	No
	Line[1]	Intensity	(1) Length of Primary Spark-Gap				(2) Length of Secondary Spark-Gap			(3) Capacity[3]				(4) Self-Induction		(5) Impedance		(6) Field Circuit Resistance	
Results	3900.68	5[2]	0.004	0.017	0.012	0.034	0.014	0.027	0.041	0.034	0.036	0.040	0.043	0.010	0.043	0.031	0.034	0.029	0.034
	04.95	7	−.004	−.003	.010	.022	−.006	−.004	.023	.022	.....	.....	.027	−.004	.027	.007	.022	−.001	.022
	13.58	5[2]	.004	.010	.010	.038	.011	.031	.042	.038	.038	.042	.041	.002	.041	.022	.038	.017	.038
	98.77	8	−.004	−.014	.007	.024	−.003	.009	.025	.024	.	.....	.030	−.002	.030	−.001	.024	.003	.024

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[1] Wave-lengths and intensities from Hasselberg's table of the arc spectrum of titanium.

[2] In the spark spectrum lines 3900.68 and 3913.58 are stronger than 3904.95 and 3998.77.

[3] For values of condenser plates in meters and microfarads, see Table III.

[4] Impedance of unknown amount.

that the average displacement for two cadmium lines increases but slowly between 48 and 70.2 meters; and Mohler remarks that "this seems to indicate that the pressure in the spark does not increase directly with the capacity, but, as indicated by Haschek and Mache, the pressure approaches a maximum value."[1] (Haschek and Mache had inclosed the spark in a receptacle and measured the pressure developed when the discharge passed. They used a spark-gap of 2 mm between brass terminals 3 mm in diameter and produced the spark by a transformer which gave "5,200 volts effective" potential.)

TABLE III.

Condenser capacities in meters and microfarads.

No. of plates of condenser	Meters	Microfarads
9	59.4	0.0066
19	125.1	0.0139
38	249.3	0.0277
77	504.3	0.0560

TABLE IV.

HORIZONTAL SPARK.

Mean displacements taken from Table I. Part of spark exposed and spark length are severally the variables. Displacements of spark lines toward red in tenth-meters: positive unless otherwise indicated.

<table>
<tr><td rowspan="8">CONDITIONS</td><td colspan="2">Plate numbers</td><td>34, 35</td><td>36, 37</td><td>38, 39</td></tr>
<tr><td colspan="2">Date of exposure</td><td>Jan. 16</td><td>Jan. 16</td><td>Jan. 16</td></tr>
<tr><td colspan="2">Length of spark-gap in mm</td><td>20</td><td>20</td><td>1</td></tr>
<tr><td colspan="2">Capacity in plates of condenser</td><td>9</td><td>9</td><td>9</td></tr>
<tr><td colspan="2">Self induction in henries</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td colspan="2">Impedance in primary transference circuit</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td colspan="2">Field circuit resistance in ohms</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td colspan="2">Fan running</td><td>No</td><td>No</td><td>No</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">LINE</td><td rowspan="2">INTENSITY</td><td colspan="3">PART OF SPARK EXPOSED</td></tr>
<tr><td>Near terminal</td><td>Near center</td><td>Near center</td></tr>
<tr><td rowspan="4">RESULTS</td><td>3900.68</td><td>5</td><td>0.058</td><td>0.023</td><td>0.026</td></tr>
<tr><td>04.95</td><td>7</td><td>0.020</td><td>0.014</td><td>.....</td></tr>
<tr><td>13.58</td><td>5</td><td>0.045</td><td>0.022</td><td>0.021</td></tr>
<tr><td>98.77</td><td>8</td><td>0.020</td><td>0.002</td><td>0.011</td></tr>
</table>

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[1] ASTROPHYSICAL JOURNAL, 9, 351, 1899.

In view of this it seems extremely improbable that an increase in capacity from 504 to 625 meters would increase the displacement from 0.043 (the maximum shift obtained by the writer for λ 3900.68—see plates 4a, 5 and 6) to 0.13 tenth-meter.

Haschek states that the transformer and induction coil give different positions for the spark lines—which, indeed, is probably the case. Difference in energy consumption is assigned as the explanation[1] of the difference in spark pressure as found by Mohler, and by Haschek and Mache.[2] This will not explain the larger displacements given by Haschek, for the writer used quite as powerful apparatus, if not more so. In Plates 20 and 21, for instance, the potential difference on the terminals of the primary circuit of the transformer was 77 volts, the current flowing 21 ampères, and the resultant power by actual measurement 1000 watts. The secondary voltage was about 10,500. Haschek's "spark was produced by a high potential transformer supplied by a primary current of 12 ampères and 100 volts, which transformed up to about 10,000 volts." Therefore difference in transformer would not be likely to produce such a difference in displacement.

Another matter may be touched upon at this point. Table IV shows that near the center of the spark gap the displacement is less than near the terminals. After discussing the work of Haschek and Mache "On the Pressure in the Spark,"[3] Haschek writes:[4]

> An explanation of the origin of spark pressure may be found in the investigation of Schuster,[5] who observed that the small particles of the metallic vapor discharged from the electrodes move with great velocity, which diminishes sharply with increasing distance from the electrodes. From this it follows that the particles crowd together toward the middle of the path of the spark, so that the pressure increases with the distance from the electrode. A conception of how the pressure affects the wave-length of the emitted light may be obtained by considering that, upon a sufficiently close approach, the particles must exert mutual forces upon each other. These

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[1] ASTROPHYSICAL JOURNAL, 14, 198, 1901.

[2] *Ibid.*, 12, 50, 1900. [3] *Ibid.*, 9, 347, 1899. [4] *Ibid.*, 14, 188, 1901.

[5] *Nature*, 57, 1899; *Phil. Trans.*, 193, A, 1899.

light-producing particles will then no longer vibrate freely, but under the influence of a dampening which causes an increase of wave-length.

This reasoning is not clear to the writer. If we are justified in assuming that the kinetic theory of gases is applicable to the metallic particles of the luminous source, we have:

$$p = \tfrac{1}{3}\, m\, n\, u^2,$$

where p is the pressure exerted by the conglomeration of the particles, m the mass of a particle, n the number of particles, and u^2 the "mean squared velocity."

Even if n increased toward the center of the spark gap, the conclusion could not be drawn that the pressure was greater at this point, for the decrease in the value of u^2 might more than compensate for the increase of n. The fact is that there are probably, in general, more glowing metallic particles near the terminals than in an equal volume at a point midway between them, as is shown (1) by the time of exposure necessary in the two cases to photograph the lines investigated—either with vertical or horizontal spark gap, this being especially true of the lines λ 3900.68 and 3913.58, which appear much enhanced near the terminals;[1] and (2) by the results obtained by Schenck[2] who states that "the principal spark lines show a tendency to shorten up close to the poles, while the arc lines go clear across the gap." Of course, we may not be justified in using the word "pressure" with reference to the spark, because in a phenomenon such as this the motion of the particles is so irregular that the term "mean squared velocity" may well be regarded as having no physical meaning. Moreover, in general, it may not be justifiable to base any line of reasoning on conclusions drawn from the kinetic theory of gases.

All that may be said is that, if increase of pressure in the spark produces an increase in the wave-length of the line, the pressure near the terminal is greater than that in the center of the spark.

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[1] Schuster states that "the metallic vapors remain luminous in the center of the spark for a longer period than near the poles." However, the intensity of illumination appears—for the characteristic spark lines at least, if not indeed for the rest as well—greater near the "pole."

[2] ASTROPHYSICAL JOURNAL, 14, 129. 1901.

To study further the effect of inserting self-induction in the discharge circuit of the condenser there was taken somewhat later a series of plates covering the region λ4200 to λ4700, one set with 0.000426 henries self-induction and the other with none.

TABLE V.

Relative positions of spark and arc lines observed with and without self-induction in the discharge circuit of the condenser. M=mean displacement of spark line.

Line	Displacement for Separate Plates					
	41	42	M	45	46	M
4443.97	−0.015	−0.029	−0.022	−0.007	−0.008	−0.007
55.48	.051	.046	.048	.003	.006	.004
68.65	.030	.033	.031	000	.006	.003

TABLE VI.

Mean displacements taken from Table V. Self-induction is the variable. Displacements in tenth-meters: positive toward the red.

Conditions	Plate numbers	41, 42	45, 46
	Date of exposure	Jan. 17	Jan. 17
	Length of spark gap in mm	1	1
	Capacity in plates of condenser	77	77
	Impedance in primary transference circuit	0	0
	Field circuit resistance in ohms	0	0
	Fan running	No	No

	Line	Intensity	Self-Induction in Henries	
			0	0.000426
Results	4443.97	6	−0.022	−0.007
	55.48	6	.048	.004
	68.65	6	.031	.003

Table V shows the agreement of the measurements made upon the members of each set; and Table VI gives the condition under which the plates were taken. It will be noticed in the case of λ4443.97 that the insertion of self-induction appears to place the line farther toward the red—an exception to the general rule found above.

The results of this brief survey of the questions considered may be summed up as follows:

1. When a spark spectrum is obtained for purposes of measurement, the conditions under which it is taken should be stated more fully than is customary at present, for the position of the lines is altered to more than a negligible degree by the condition of the electric circuit as to capacity, self-induction, resistance in field circuit of alternator, and impedance in primary circuit of transformer.

2. Different parts of the spark give spectra in which the lines have not only different relative intensities, but different wave-lengths.

That the wave-lengths depend upon the capacity and the apparatus used, whether induction coil or transformer, has been known for some time. That self-induction alters the position of the lines, and that the part of the spark exposed enters as important factors, are facts which had not come to the writer's notice.

3. Such large displacements, as are given by Haschek for the lines of the *Ti* spectrum have not been found here.

It must be clearly understood that the grating used is not one which possesses a dispersion fully adequate for an accurate quantitative study of the question in hand; and that, with the dispersion given, the limit of accuracy of measurement lies far too near the magnitude of the effects studied. However, the collateral evidence is so strong that the results here given are undoubtedly qualitatively correct. Moreover, it appears impossible to attribute the persistent and regular changes in the positions of the spark lines to mechanical motion in the apparatus, unequal illumination of the grating, heating of the slit, errors in measurement, or, in short, to any other causes than those given

MINOR CONTRIBUTIONS AND NOTES.

THE NEW STAR IN *GEMINI.*

TELEGRAPHIC announcement of the discovery on March 16 of a new star in *Gemini* by Turner (presumably on the Oxford photographs) was received at the Yerkes Observatory on the afternoon of March 27. The same evening the star was observed with the forty-inch refractor. Its conspicuous red color was at once explained by the great intensity of the $H\alpha$ line, as observed by Mr. Ellerman and the writer with a direct vision spectroscope. Very bright lines in the yellow and blue were clearly visible on a faint background of continuous spectrum. The star thus presented the familiar characteristics of *Novæ.*

The region of the *Nova* had been photographed with the two-foot reflector by Mr. Parkhurst on February 21, 1903, for the purpose of charting the field around the variable star 2404 *X Geminorum*, which lies two-thirds of a degree east. The exposure time was 20 minutes, from $8^h\ 22^m$ to $8^h\ 42^m$ C. S. T. After the receipt of the telegraphic announcement of Professor Turner's discovery, Mr. Parkhurst carefully examined the region of the *Nova* on this plate. What appeared to be an image of the *Nova* was found. It is a little brighter than the fifteenth magnitude, the faintest stars visible in the vicinity being about half a magnitude fainter. Careful comparison with similar plates taken since the *Nova* brightened, and also with the sky as seen in the large telescope, indicates that the star photographed is either the *Nova* or a fifteenth magnitude star within three seconds of arc of the place. The comparison certainly shows that the *Nova* was not brighter than the fifteenth magnitude on February 21.

The region of the *Nova* was photographed with the two-foot reflector by Mr. Pease on March 28 and 29 with a total exposure of 8¾ hours (Plate XXI). As the conditions were fairly good during the exposure of this photograph, it seems probable that no bright nebulosity, like that surrounding *Nova Persei*, existed at this time in the vicinity of *Nova Geminorum*.

Position.— Micrometric measures with the 40-inch refractor by Professor Barnard gave the following positions for the new star with respect to *B. D.* 29°1342 (8.2 mag.):

Date	*Nova*—Star	
March 27....	$\Delta\alpha$ $-2^{m}\ 21^{s}.84$	$\Delta\delta$ $+5'\ 57''.29$
March 30....	$-2\ \ 21.76$	$+5\ \ 57.25$
	$-2\ \ 21.80$	$+5\ \ 57.27$

In the observations of March 27, an intermediate star was used in both $\Delta\alpha$ and $\Delta\delta$, and on the 30th in $\Delta\alpha$.

Mean place of comparison star for 1900.0	Authority.
$\alpha = 6^{h}\ 40^{m}\ 10^{s}.79$; $\delta = +29^{\circ}\ 56'\ 42''.05$.	Leiden *A.G.C.* 2813 and Cambridge *A.G.C.* 3482.

It was observed twice at Leiden and three times at Cambridge; the declinations differ by $1''.7$, which does not appear to be due to motion. These two positions were weighted according to the number of observations.

The following position results for the *Nova:*

$$1900.0\quad \alpha = 6^{h}\ 37^{m}\ 48^{s}.99.\quad \delta = +30^{\circ}\ 2'\ 39''.3.$$

The star is of a strong red color — redder than *B. D.* + 29°.1342.

Micrometric measures have been made of the small stars near the *Nova* to form an accurate chart for detection of possible motion in the *Nova*. The measures so far made are given below. The stars may be identified from the accompanying drawing (Fig. 1) showing the field immediately surrounding the *Nova.*

Nova and $12^{m}.3$ star following = No. 1.

1903, March 30.......	104°.82	32''.21
April 4.........	105.22	32.52
	105.02	32.36

Nova and $12^{m}.6$ star South = No. 2.

1903, March 30.......	169°.21	45''.66

Nova and $14^{m}.5$ star North = No. 3.

1903, March 30.......	341°.61	55''.69

Nova and $12^{m}.5$ star preceding = No. 4.

1903, March 30.......	196°.15	84′.93
April 4.........	196.30	85.15
	196.22	85.04

Nova and $12^{m}.5$ star North = No. 5.

1903, March 30.......	313°.86	99′.87
April 4.........	313.90	99.93
	313.88	99.90

Nova and 12^{m} star North = No. 6

1903, March 30	16°.98	102′.81
April 4.........	17.45	103.00
	17.21	102.90

POSITIONS OF THE SMALL STARS, REFERRED TO THE MEAN EQUINOX OF 1900.0.

	R. A.			Dec.		
No. 5.....	6^{h}	37^{m}	$43^{s}.44$	+30°	3′	48″.5
4.....	6	37	47.16	+30	1	17.6
3.....	6	37	47.64	+30	3	32.1
2.....	6	37	49.65	+30	0	54.5
6.....	6	37	51.33	+30	4	17.6
1.....	6	37	51.40	+30	2	30.9

Focus.—The following observations made by Professor Barnard show that the focus of the *Nova* with the forty-inch refractor did not differ appreciably from that for the comparison star:

Inches
March 27 *Nova* focus 2.12 (4 obs.)
B.D. +30°.1314 " 2.10 (5 obs.)
Nova − star = +0.02 = +0.51 mm
March 30 *Nova* focus 2.13 (9 obs.)
B.D. +30°.1314 " 2.15 (9 obs.)
Nova − star = −0.02 = −0.51 mm

When in the best focus there was a decided glow about the star for some 2″ or 3″, which was of a crimson color. This was not present with the other stars. By drawing the eyepiece out, a small, well-defined image of the star was formed of about the tenth magnitude and about 0.'1 in diameter. It was sharply defined and of a beautiful crimson color — far more vivid than Hind's celebrated crimson star. The *Nova* was surrounded by a pale, grayish blue halo 3.'8 in diameter by measurement. This phenomenon was not present when other stars were thrown out of focus.

Five very accordant settings were made for the focus for this crimson image, giving focus = 2.51 inches. This, compared with the observations for the true focus for this star on the same date, showed that this second image, one and a half magnitudes less than the other, was formed 0.38 inch (9.6 mm) outside the proper focus for the *Nova*. This was undoubtedly due to the predominance of the bright *Hα* line in the light of the *Nova*.

Magnitude.—The photometric magnitudes of the *Nova*, as measured on seven nights by Mr. Parkhurst with an equalizing wedge photometer attached to the twelve-inch refractor and six-inch reflector, are as follows:

PHOTOMETRIC MAGNITUDES OF *NOVA GEMINORUM* ON HARVARD COLLEGE OBSERVATORY SCALE.

(To express on Potsdam scale, add 0.20 mag.)

Date.	G. M. T.	Mag.
1903, March	27.715	8.51
	28.636	8.71
	29.603	8.85
	29.650	8.91
	30.673	8.76
	31.588	8.89
April	3.564	8.91 ±
	4.583	8.96

Measured from four standard stars; mean residual from separate stars, 0.03 mag.

Spectrum.—As neither the position nor the physical characteristics of the bright lines could be determined satisfactorily by visual observations, two of the prisms of the Bruce spectrograph were removed, and a short camera attached for use with a single prism. The camera lens employed was a Unar, series Ib, No. 7, kindly loaned by the Bausch & Lomb Optical Co. pending the construction of a special short focus doublet. A mounting for the camera was made in the instrument shop on March 28, and the spectrum of the *Nova* was photographed on that evening by Professor Frost and Mr. Adams. The photograph, which is reproduced in Fig. 2, was taken at $15^h\ 40^m$ G. M. T. (middle of exposure), and was exposed for $3^h\ 12^m$. A Cramer isochromatic plate was used, without the correcting lens. Titanium was employed for the comparison spectrum, supplemented by helium, the spectrum of which was photographed on another plate immediately after the end of the exposure for the star.

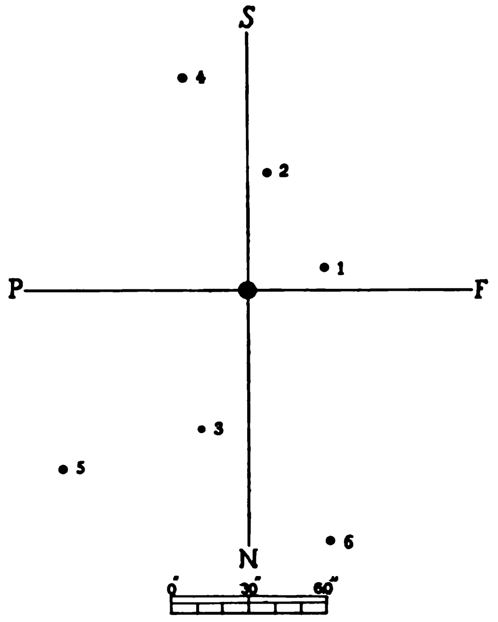

FIG. 1.—Stars near the *Nova*.

Professor Frost's study of this photograph shows that the most conspicuous features are the very strong bright band extending from about λ 4598 to λ 4696 (mean at λ 4647), and the very strong *Hβ* line, extending from λ4839 to λ4886 (mean at λ4862). There appeared to be two narrow bright maxima near the less refrangible end of *Hβ*, at λ4877 and λ4882. At the less refrangible end of the plate there are two fairly strong bands, one extending from λ 5647 to λ 5685 (mean at λ 5666), the other extending from λ 5729 to λ5775 (mean at λ5752). The less refrangible of these lines is rather sharply bounded on the violet side, suggesting the presence of a dark band. The lack of sensitiveness of the plate near λ 5000 may account for the absence of the band near λ 5016, which, though found in the spectra of *Nova Aurigae* and *Nova Persei*, is exceedingly faint in *Nova Geminorum*. *Hγ*, though hardly measurable, is visible on the plate as a very faint band merging into a brighter band which extends from λ 4347 to λ 4371 (mean at λ 4359). The intensity of this part of the spectrum was greatly reduced through the absence of the correcting lens, and the slit was not in the focal plane of the forty-inch telescope for this region. This probably accounts for the decided faintness of *Hγ* as compared with $H\beta$, but in any case $H\gamma$ would appear to be distinctly fainter than λ 4359.

The spectrum of *Nova Geminorum* thus corresponds with the spectra of *Nova Persei* and *Nova Aurigae* in their later stages of development, particularly with respect to the relative intensity of the bands observed, all of which were present in both of these stars. After the transformation of the spectrum of *Nova Aurigae* into that of a nebula, in August 1892, the intensities of λλ 4358, 4640, 4863, and 5750 were estimated by Campbell as 8, 7, 10, and 10 respectively, and were only exceeded by the chief nebular lines λ 5007 and λ 4959 with intensities of 100 and 30. On the negative of the spectrum of *Nova Geminorum* the very faint bright band in the region of the principal nebular lines is too weak for measurement.

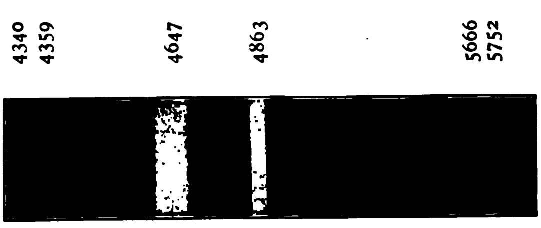

FIG. 2.—Spectrum of *Nova Geminorum*, March 28, 1903.

Visual observations of the *Nova* have been made with a single ocular prism, or direct vision train, on each available night since March 27, but no changes sufficiently obvious to be noticed with such small dispersive power have been observed.

GEORGE E. HALE.

YERKES OBSERVATORY,
April 6, 1903.

NOVA GEMINORUM BEFORE ITS DISCOVERY.[1]

ON March 27, 1903, a cable message was received from Professor Kreutz, of Kiel, stating that an object which was probably a new star, but was possibly a variable, had been discovered by Professor Turner. Also, that on March 16 it was of the magnitude 8.0, while on February 16 it had not been seen (presumably on a photograph). Its apparent place was R. A. $6^h\ 37^m\ 48^s$, Dec. + 30° 4′. The grant from the Carnegie Institution permitted an examination to be made of the early photographs of the Henry Draper Memorial, and furnished the history of this object from its first appearance to the present time. An excellent photograph of the region, taken 1903, March $1^d\ 15^h\ 3^m$, G. M. T., showed stars of the magnitude 11.9, but no trace of the *Nova* was

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[1] *Harvard College Observatory Circular* No. 70.

visible. A similar result was found from sixty-seven plates, the first taken March 3, 1890, the last on February 28, 1903, although nearly all of these plates showed stars fainter than the twelfth magnitude. One or more of these photographs were taken on each intermediate year. It did not therefore seem necessary to examine the other early plates of this region, a hundred or more in number. A plate taken 1903, March 2^d 13^h 19^m, showed stars of the ninth magnitude, but no trace of the *Nova*. The evenings of March 3, 4, and 5 were cloudy, but on a plate taken March 6^d 14^h 28^m, an object of the magnitude 5.08 appears in the given place. Plates taken on several later nights showed that the magnitude was gradually diminishing, as appears in Table I, which gives in successive columns the date, the Greenwich Mean Time, the photographic magnitude of the *Nova*, and the initial of the observer. F. denotes Mrs. Fleming and L. Miss Leland.

The photograph of March 6 has especial value, since, so far as is known, it contains the first photograph of the *Nova*. The image is on the very edge of the plate, and accordingly was compared with fifteen other stars at about the same distance from the center of the plate. The *Nova* was compared twice with each star by each observer. The value of the grade was much larger than usual, and equaled 0.21 and 0.33 for the two observers. The mean result for all was magnitude 5.08, with an average deviation, for the separate stars, of ± 0.26. The magnitude on each of the other dates given in the table was found by comparison with six stars whose brightness was nearly equal to that of the *Nova*. These magnitudes were derived assuming that the photometric and photographic magnitudes were nearly the same for stars whose spectra were of the first type.

TABLE I.

PHOTOGRAPHIC MAGNITUDES.

Date	G. M. T.	Mag.	Obs.	Date	G. M. T.	Mag.	Obs.
	h. m.				h. m.		
1903 March 1	15 3	<11.4	L.	1903, March 14	14 14	7.42	F.
2	14 31	< 9.5	F.	14	14 14	7.34	L.
6	14 28	4.97	F.	14	16 20	7.32	F.
6	14 28	5.20	L.	14	16 20	7.34	L.
11	15 18	6.76	F.	15	13 44	7.27	F.
12	14 25	7.06	F.	15	14 53	7.57	F.
12	15 25	7.16	F.	15	14 53	7.46	L.
13	14 52	7.12	F.	25	13 26	7.94	L.
13	14 52	7.17	F.	25	13 39	8.08	F.

The evening of March 27 was cloudy and also the early part of March 28. One plate, however, taken on the latter date, gave the magnitude 8.34. Several photographs were taken on March 29, 31, and April 1, and gave the mean magnitudes 8.24, 8.24, and 8.25. These magnitudes are based upon the results given in Table II, which contains the designations, ***Durchmusterung*** numbers, rectangular coordinates expressed in seconds of arc with the *Nova* as an origin, and provisional photographic magnitudes of a sequence of comparison stars. It is probable that the fainter stars are really fainter than these magnitudes indicate, but the latter will serve to determine the relative changes in the *Nova* as it grows fainter, and thus render the results of different observers comparable. All the magnitudes can later be reduced to an absolute scale. They also serve to compare the faintest stars shown on early plates. Thus, the photograph taken March 1, 1903, shows star *t*, and also stars at least a tenth of a magnitude fainter. Star *u* does not appear. Hence this plate shows stars of the magnitude 11.9 and brighter.

The last plate in Table I is of interest, since it was taken with an objective prism, and accordingly shows the spectra of the *Nova* and of the adjacent stars. Six bright lines are shown in the spectrum of the *Nova*, whose designations, assumed wave-lengths, and intensities, calling the intensity of the line $H\gamma$, *10*, are as follows: $H\zeta$, $\lambda 3889$, *1*; $H\epsilon$, $\lambda 3970$, *3*; $H\delta$, $\lambda 4102$, *8*; $H\gamma$, $\lambda 4341$, *10*; —, $\lambda 4643$, *11*; $H\beta$, $\lambda 4862$, *9*.

TABLE II.

COMPARISON STARS.

Des.	*B. D.*	*x*	*y*	Mag.	Des.	*B. D.*	*x*	*y*	Mag.
		″	″				″	″	
a	+30° 1318	+ 716	+3187	7.28	*p*	......	+ 4	+368	11.19
b	+30° 1300	......	......	7.76	*q*	......	+308	−132	11.41
c	+30° 1314	+ 274	+1949	7.98	*r*	......	−404	−278	11.63
d	+30° 1320	+1021	+ 878	8.50	*s*	......	+359	+345	11.73
e	+29° 1342	+1843	− 347	8.82	*t*	......	−224	+176	11.78
f	+30° 1316	+ 643	+ 552	9.14	*u*	......	+467	+145	12.08
g	+30° 1306	−1006	+ 142	9.36	*w*	......	−254	+242	12.23
h	... .	+ 504	+ 289	9.71	*x*	......	−268	+ 92	12.45
	... ...	+ 504	+ 297		*y*	......	+270	+ 16	12.70
k	+30° 1302	−1923	+ 231	9.93	*z*	......	+186	− 64	12.95
l	+30° 1309	− 456	+ 53	10.13	α	......	+ 31	+ 97	13.05
m	+30° 1317	+ 638	− 327	10.41	β	......	− 24	− 76	13.35
n	... .	− 311	− 47	10.66	γ	......	+ 31	− 8	13.53
o	... .	+ 544	+ 197	11.01					

From this it appears that the spectrum resembles that of *Nova Sagittarii* on April 19, 1898. No dark lines are visible, but this is perhaps owing to the small dispersion.

The same lines, and having nearly the same intensities, appeared on similar photographs taken on March 29, 31, and April 1. They also showed the additional nebula line, λ 5003, which has the intensity *2* or *3*, and is certainly brighter than *Hζ*. This line does not appear on the plate taken March 25, and indicates the first step in the change into a gaseous nebula. Three additional bright lines were detected in the later photographs, whose estimated wave-lengths are about λ 4176, 4240, and 4462.

In the other new stars the appearance of line 5003 was followed by the diminution in intensity of the line *Hβ*, and the appearance and rapid increase in the nebula line, near *Hζ*, which finally became the strongest line in the spectrum.

A most important question in connection with the appearance of new stars is whether such objects can come and go without detection by astronomers. Since the Henry Draper Memorial was established, nine new stars have been discovered. Six of them, *Nova Persei* No. 1, *Nova Normae*, *Nova Carinae* No. 2, *Nova Centauri*, *Nova Sagittarii*, and *Nova Aquilae*, were found in the regular examination of the Draper Memorial photographs, and probably all of them would otherwise have escaped detection. Two, *Nova Aurigae* and *Nova Persei* No. 2, were bright, and were found visually by Dr. Anderson. The first of these might have escaped detection here, although numerous early charts were obtained which showed that it was visible to the naked eye during seven weeks before its discovery. The spectrum of Turner's *Nova* is so conspicuous on the plate taken on March 25 that when this plate was developed and examined it would doubtless have been found on it here, but for the prompt discovery and announcement by Professor Turner.

EDWARD C. PICKERING.

APRIL 3, 1903.

A LIST OF FOUR STARS WHOSE VELOCITIES IN THE LINE OF SIGHT ARE VARIABLE.[1]

THE following four spectroscopic binaries, discovered with the Mills Spectrograph, are additional to the thirty-eight binaries already announced:

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[1] *Lick Observatory Bulletin* No. 31.

ν Andromedae ($\alpha = 0^h\,44^m$; $\delta = +40^\circ\,32'$).

The variable velocity of this star was discovered from the second plate. Three observations have been secured, as follows:

Date	Velocity	Measured by
1902, October 8	− 17 km	Curtis
November 5	− 76	Curtis
1903, January 14	+ 49	Curtis

The spectrum of this star shows very few lines. The *H*γ line is very broad, but the lines due to helium are much better and admit of fairly accurate measurements.

π⁴ Orionis ($\alpha = 4^h\,46^m$; $\delta = +5^\circ\,26'$).

The variation in velocity was discovered from the second plate, the observations being as follows:

Date	Velocity	Measured by
1902, October 6	+ 43 km	Curtis
1903, January 4	± 0	Curtis
January 12	+ 6	Curtis

The spectrum is very similar to that of *ν Andromedae.*

σ Geminorum ($\alpha = 7^h\,37^m$; $\delta = +29^\circ\,7'$).

The change in velocity was shown in the second plate of this star. The observations are as follows:

Date	Velocity	Measured by
1902, March 16	+ 74 km	Reese
1903, January 12	+ 12	Reese
January 13	+ 9	Reese
February 15	+ 69	Curtis

The lines in the spectrum of this star, though numerous, are rather hazy. Still they admit of trustworthy measurements.

ι Argus ($\alpha = 8^h\,3^m.3$; $\delta = -24^\circ\,1'$).

Director Campbell requests me to announce also the variable velocity of ι *Argus*, discovered by him in 1898 from the second plate.

Date	Velocity	Measured by
1897, February 23	+41.9 km	Reese
1898, February 21	+49.5	Reese
1899, April 12	+49.8	Reese
April 13	+50.3	Reese
1901, April 9	+42.3	Reese
1902, February 18	+46.3	Reese

H. M. Reese.

February 21, 1903.

A STAR WITH A GREAT RADIAL VELOCITY.[1]

The star ϕ^2 *Orionis* ($\alpha = 5^h\ 31^m$; $\delta = +9^\circ\ 15'$) is interesting on account of its great velocity in the line of sight. The observations are as follows:

Date	Velocity	Measured by
1902, October 28	+ 94 km	Curtis
November 24	+102	Curtis
December 30	+ 96	Curtis

Although the spectrum shows reasonably good lines, it is not likely that the range of eight kilometers in these measurements indicates a real variability in the star's motion, for the second plate was much underexposed.

H. M. Reese.

February 19, 1903.

THE SPECTRUM OF THE NEBULOSITY SURROUNDING *NOVA PERSEI*.[2]

The remarkable changes of position and brightness observed in the nebulosity around *Nova Persei* have made it desirable to accumulate as much evidence as possible bearing upon the nature of these phenomena.

Unfortunately, physical observations were not attempted during the earlier stages, when the nebulosity was brighter. At the time of the discovery of these changes, it seemed unlikely that any satisfactory

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[1] *Lick Observatory Bulletin* No. 31.

[2] *Lick Observatory Bulletin* No. 33.

spectroscopic observations could be obtained, owing to the faintness of the nebulosity. The great uncertainty as to the real nature of the changes and the almost entire lack of positive evidence seemed to warrant the attempt, notwithstanding the difficulties.

A small slit-spectrograph, to be used with the Crossley Reflector, was designed especially for the problem. Both collimator and camera lenses are single and of quartz; the prism is also of quartz, the refracting angle being 50°. Following are the constants of the spectrograph, including those of the telescope:

Aperture of lenses and prism - - - - - - -	1⅛ inches
Focal length of collimator and camera lenses - - -	6 inches
Refracting angle of prism - - - - - - - - -	50° 14′
Aperture of Crossley Reflector - - - - - -	36¼ inches
Focal length of Crossley Reflector - - - - - -	210 inches

The prism and lenses were mounted directly in frames of brass and attached to the body of the spectrograph, which was constructed of Spanish cedar. A reflecting slit was used, and guiding was accomplished by means of the reflected image of the *Nova* viewed in a small telescope. The nebular spectrum occupied the central 0.2 inch of the slit, on either side of which was photographed a comparison spectrum of hydrogen. The slit-width was reduced to 0.002 inch for the comparison spectrum, which was inserted for from 2ˢ to 5ˢ each night at about the middle of the exposure.

The photographs of the *Nova* in August and September 1902, with exposures of 7 to 11 hours, showed only condensation *D* with any certainty. No attempt was made, therefore, to study any other portion of the nebula. The slit was placed approximately parallel to a circle of declination, and by estimation across the densest part of condensation *D*. This region was free from small stars. The region covered was 1½′ south and from 1′ west to 4′ west of the *Nova*.

Under the above conditions and with a slit-width of 0.006 inch, a negative was obtained with the following exposures:

Duration		Remarks
1902, October 31,	$7^h\ 40^m$	Seeing 2; sky good.
November 1,	9 4	Seeing 3; haze in the beginning.
November 2,	8 0	Seeing 3; some haze in the beginning; stopped by clouds.
November 4,	9 25	Seeing 3; sky good.
Total,	$34^h\ 9^m$	

The resulting negative shows a very faint spectrum extending from $H\beta$ to about λ 360. The length of the spectrum is 0.11 inch. There is no evidence of flexure in the spectrograph, nor of any change in the position of the plate during the exposure. As the exposure on October 31 had been carried through the first traces of dawn, a negative was made, later, under as nearly the same conditions as possible, to make sure that the spectrum obtained was not that of the sky. No trace of any sky spectrum was found on this plate. Another plate which had been exposed in the brighter dawn to obtain a faint spectrum of the sky for comparison, showed that the sky spectrum was unlike that of the nebula which had been obtained. With such low dispersion the sky spectrum between $H\beta$ and K is divided into two bands of almost equal extent and intensity by the weaker region (full of absorption lines) at G. These and other considerations seem to leave no doubt that the spectrum obtained is that of the nebulosity.

In the spectrum of the *Nova* nebula fully three-fourths of the light is condensed in the region extending from $H\beta$ to $H\gamma$; above $H\gamma$ the spectrum is extremely faint, and is lacking entirely from about λ 380 to λ 390. In the upper part of the spectrum there appear to be traces of two lines, one almost coincident with $H\delta$ and the other at about λ 370. They are so extremely faint, however, that their existence cannot be affirmed with certainty.

If the above interpretation is correct, the spectrum of condensation *D* resembles that of the *Nova* during the first few days of its great brightness much more than it does that observed since July 1901. So far as can be told from the low dispersion used and the weak spectrum recorded, the general appearance of the spectrum of the nebula below λ 380 agrees very well with the spectrum of the *Nova* obtained by Campbell and Wright in February 1901. With the conditions under which their observations were made most of the light of the *Nova* would be included in the region between $H\beta$ and $H\gamma$, and the region between λ 380 and λ 390 would be too weak to show in a faint spectrum. This is also true of the region below $H\beta$. As no early observations of the spectrum of the *Nova* high up in the violet have been published, it is impossible to make any comparisons between the two spectra in this region, where some lines are suspected in the nebulosity.

The spectrum of the nebulosity does not agree with that of the *Nova* observed since July 1901. The strongest region in the spectrum of the nebulosity may possibly be made up of the lines between $H\beta$ and $H\gamma$ which the low dispersion failed to separate in a spectrum so weak, although this seems improbable. The positions of the two suspected lines at λ 410 and λ 370 do not agree at all, however, with the strongest lines in the later spectrum of the *Nova*. There are certainly no traces in the nebulosity of any lines in the positions of those observed in the *Nova* at λ 387 and λ 397 by Campbell and Wright,[2] nor at λ 346, where a very strong line was photographed by Mr. Stebbins,[1] with the Crossley Reflector. These lines are the strongest in the photographic spectrum of the *Nova* since July 1901.

The spectrum obtained is certainly not the ordinary bright-line spectrum of the nebulæ. The suspected lines at λ 410 and λ 370 may be nebular lines which occupy approximately these positions. The region between *Hβ* and *Hγ*, however, is not at all like the characteristic nebular spectrum, where *Hβ* and *Hγ* (and occasionally λ 469) are the only strong lines. If the ordinary nebular spectrum is present at all, it is in conjunction with another spectrum, probably continuous, extending from λ 434 to λ 487.

To still further test the identity of the spectrum secured, three negatives of the spectrum of the *Nova* were obtained on February 17, 1903, with the same spectrograph. Exposures of 10, 30, and 60 minutes were given. Ten minutes barely sufficed to give a distinguishable spectrum. One hour gave a spectrum showing the five principal lines between λ 387 and λ 471. There are traces of the chief nebular line, and a very faint spectrum up in the ultra-violet. The relative intensities of the lines are not very different from those obtained in September and October 1901, by Mr. Stebbins with the small slitless spectrograph attached to the Crossley Reflector.

A comparison of the spectrum of the *Nova* on February 17, 1903, and that of the nebulosity, shows that they are not identical. The line at λ 387, which is one of the strongest in the spectrum of the *Nova*, has no counterpart whatever in the nebula. It cannot be made to coincide with the slight strengthening in the nebula at λ 370.

The conclusions are, therefore, that the spectrum of condensation *D* observed in November 1902, is not the spectrum of a gaseous nebula; that it is not the spectrum of the *Nova* since the latter has become nebular; and that it more nearly resembles the spectrum of the *Nova* during the first few days of its outburst. The question as to what epoch in the star's history the spectrum of the nebulosity should conform, if the light were reflected, is a difficult one to decide with the data in our possession. This is particularly true in the case of con-

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[1] *Lick Observatory Bulletin* No. 8.

densation *D*. Some knowledge of the real distance and direction of this mass from the star, or spectroscopic observations at considerable intervals, would aid materially in the solution.

The preceding spectroscopic evidence is not inconsistent with the theory that the light of condensation *D*, at least, is reflected light emitted by the *Nova at the time of its greatest brightness;* but is not strong enough to establish this theory in the face of conflicting indications already pointed out.

The spectrum of the thirteenth-magnitude star at approximately the position-angle of 245° and 4½′ distant from the *Nova* is also shown on the negative, this star having occasionally crossed the slit. Its spectrum appears to be continuous, and extends from $H\beta$ to $H\gamma$.

I am indebted to Dr. Campbell for suggestions as to the construction of the spectrograph, and to Dr. H. D. Curtis and Fellows R. H. Curtiss and C. A. G. Weymouth for assistance in making the observations.

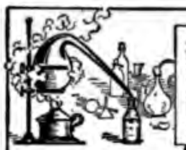
C. D. PERRINE.

MARCH 2, 1903.

THE SNOW HORIZONTAL TELESCOPE.

I AM glad to be permitted to announce that Miss Helen E. Snow, of Chicago, has provided for the reconstruction of the coelostat reflecting telescope of the Yerkes Observatory as a memorial to her father, the late George W. Snow. Through Miss Snow's generosity it will be possible to build the telescope in permanent and substantial form, and to provide it with solar and stellar spectrographs, spectroheliographs, and other important accessories. The great superiority of the new instrument will amply compensate for the delay occasioned by the fire of last December.

GEORGE E. HALE.

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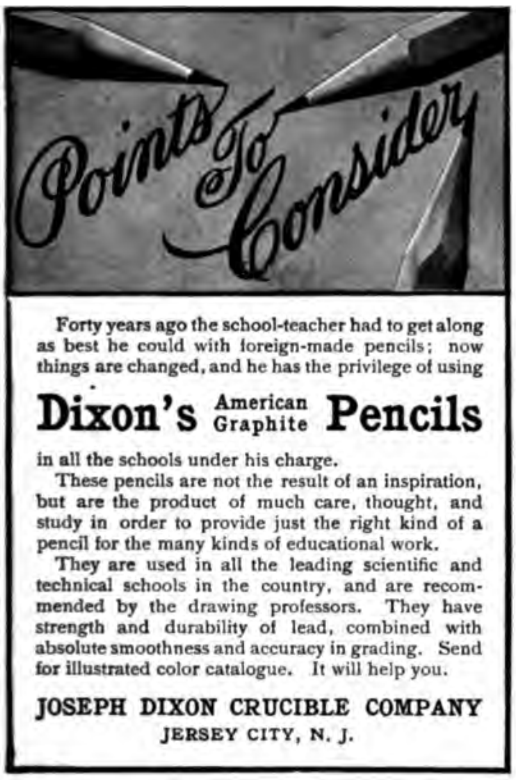

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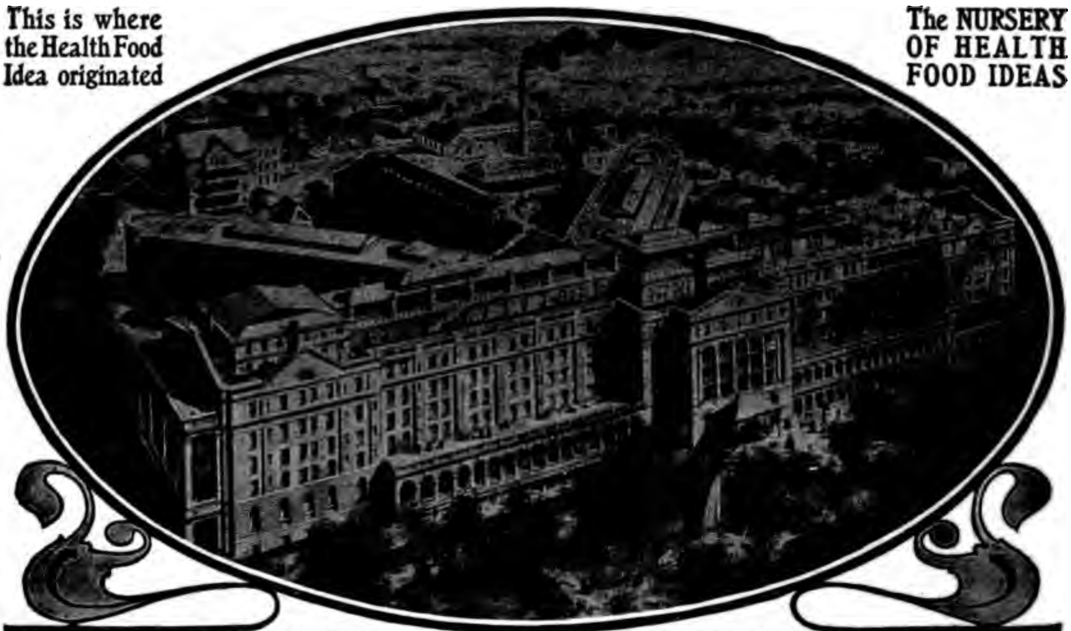

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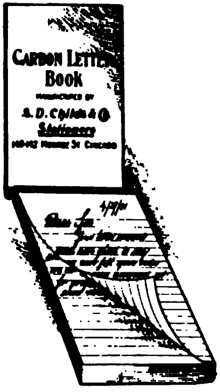
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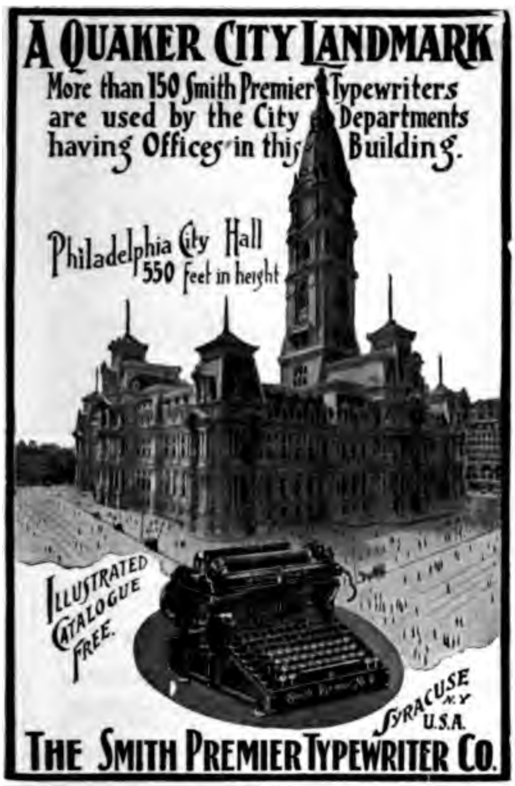

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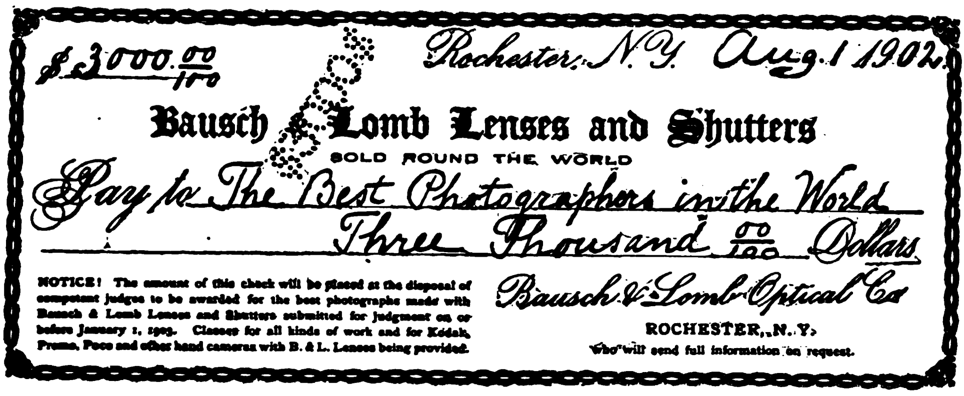

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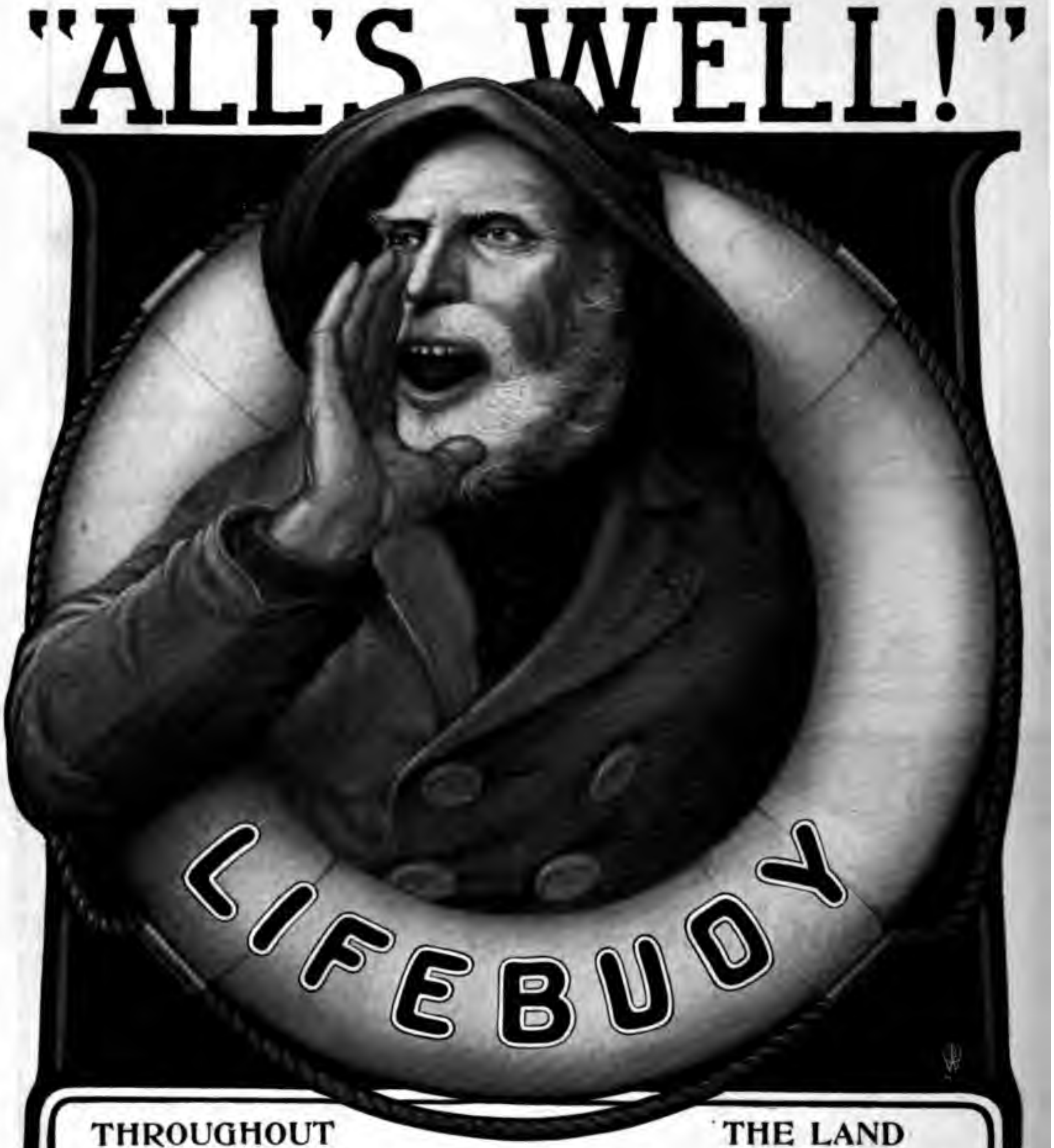

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VOLUME XVII JUNE 1903 NUMBER 5

THE PRESSURE DUE TO RADIATION.[1]

By E. F. NICHOLS and G. F. HULL.

As EARLY as 1619 Kepler[2] announced his belief that the solar repulsion of the finely divided matter of comets' tails was due to the outward pressure of light. On the corpuscular theory of light Newton[3] considered Kepler's idea as plausible enough, but he was of the opinion that the phenomenon was analogous to the rising of smoke in our own atmosphere. In the first half of the eighteenth century DeMairan and DuFay[4] contrived elaborate experiments to test this pressure of light theory in the laboratory, but, because of the disturbing action of the gases surrounding the illuminated bodies employed in the measurements, they obtained wholly confusing and contradictory results. Later in the same century Rev. A. Bennet[5] performed further

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[1] Presented to *the American Academy of Arts and Sciences*, April, 1903.

[2] DEMAIRAN, *Traité physique et historique de l'Aurore boréale* (2d ed.), pp. 357, 358. Paris, 1754.

[3] *Isaaci Newtoni Opera quae Existant Omnia.* Samuel Horsley, LL.D., R.S.S., Tom. III, pag. 156. Londinium, 1782.

[4] DEMAIRAN, *loc. cit.*, p. 371. This treatise contains also the accounts of still earlier experiments by Hartsoeker, p. 368, and Homberg, p. 369. The later experiments are of more historic than intrinsic interest.

[5] A. BENNET, *Phil. Trans.*, p. 81, 1792.

experiments, but could find no repulsive force not traceable to convection currents in the gas surrounding the body upon which the light was projected, due in his opinion to the heating effect of the rays. Finding no pressure due to radiation, he made the following unique suggestion in support of the wave theory of light:

> Perhaps sensible heat and light may not be caused by the influx or rectilinear projection of fine particles, but by the vibrations made in the universally diffused caloric or matter of heat or fluid of light. I think modern discoveries, especially those of electricity, favor the latter hypothesis.

In the meantime Euler,[1] accepting Kepler's theory attributing the phenomenon of comets' tails to light pressure, had hastened to the support of the wave theory by showing theoretically that a longitudinal wave motion might produce a pressure in the direction of its propagation upon a body which checked its progress. In 1825 Fresnel[2] made a series of experiments, but arrived at no more definite conclusion than that the repulsive and attractive forces observed were not of magnetic nor electric origin.

Crookes[3] believed in 1873 that he had found the true radiation pressure in his newly invented radiometer, and cautiously suggested that his experiments might have some bearing on the prevailing theory of the nature of light. Crookes's later experiments and Zöllner's[4] measurements of radiometric repulsions showed that the radiometric forces were in some cases 100,000 times greater than the light pressure forces with which they had been temporarily confused. Zöllner's experiments are among the most ingenious ever tried in this field of work, and he missed the discovery of the true radiation pressure by only the narrowest margin. An excellent bibliography of the whole radiometric literature is given by Graetz,[5] and an account of some of the older experiments not mentioned above is given by Crookes.[6]

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[1] L. EULER, *Histoire de l'Académie royale de Berlin* (2), p. 121, 1746.

[2] A. FRESNEL, *Ann. Chem. et Phys.*, 29, 57, 107, 1825.

[3] W. CROOKES, *Phil. Trans.*, p. 501, 1873.

[4] F. ZÖLLNER, *Pogg. Ann.*, 160, 156, 296, 459, 1877.

[5] L. GRAETZ, *Winkelmann's Handbuch der Physik*, 2*b*, p. 262. Breslau, 1896.

[6] W. CROOKES, *loc. cit.*, p. 501.

In 1873 Maxwell,[1] on the basis of the electromagnetic theory, showed that if light were an electromagnetic phenomenon, pressure should result from the absorption or reflection of a beam of light. After a discussion of the equations involved, he says: "Hence in a medium in which waves are propagated there is a pressure in the direction normal to the waves and numerically equal to the energy in unit volume." Maxwell computed the pressure exerted by the Sun on the illuminated surface of the Earth, and added:

> It is probable that a much greater energy of radiation might be obtained by means of the concentrated rays from an electric lamp. Such rays falling on a thin metallic disk, delicately suspended in a vacuum, might perhaps produce an observable mechanical effect.

Apparently independent of Maxwell, Bartoli[2] announced in 1876 that the Second Law of Thermodynamics required the existence of a pressure due to radiation numerically equal in amount to that derived by Maxwell. Bartoli's reasoning holds for all forms of energy streams in space, and is of more general application than Maxwell's equations. Bartoli contrived elaborate experiments to verify this theory, but was balked in the search, as all before him had been, by the complicated character of the gas action, which he found no way of eliminating from his experiments.

After Bartoli's work, the subject was dealt with theoretically by Boltzmann,[3] Galitzine,[4] Guillaume,[5] Heaviside,[6] and more recently by Goldhammer.[7] Fitzgerald,[8] Lebedew,[9] and Hull[10]

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[1] J. C. MAXWELL, *A Treatise on Electricity and Magnetism* (1st ed.), **2**, 391. Oxford, 1873.

[2] A. BARTOLI, *Sopra i movementi prodotti della luce et dal calorie*, Florence, Le Monnier, 1876; also *Nuovo Cimento*, **15**, 193, 1884.

[3] L. BOLTZMANN, *Wied. Ann.* **22**, 31, 291, 1884.

[4] B. GALITZINE, *Wied. Ann.*, **47**, 479, 1892.

[5] CH. ED. GUILLAUME, *Arch. de Gen.* (3), **31**, 121, 1894.

[6] O. HEAVISIDE, *Electromagnetic Theory*, **1**, 334. London, 1893.

[7] D. A. GOLDHAMMER, *Ann. der Phys.*, **4**, 834, 1901.

[8] G. F. FITZGERALD, *Proc. Roy. Soc. Dub.*, 1884.

[9] P. LEBEDEW, *Wied. Ann.*, **45**, 292, 1892; ASTROPHYSICAL JOURNAL, **14**, 155, 1902.

[10] G. F. HULL, *Trans. Astron. Soc. Toronto*, p. 123, 1901.

have discussed the bearing of radiation pressure upon the Newtonian law of gravitation, with special reference to the repulsion of comets' tails by the Sun. The theory of radiation pressure, combined with the known properties in negative electrons, has recently been more or less speculatively applied by Arrhenius[1] to the explanation of many cosmical and terrestrial phenomena, among which the following may be mentioned: the solar corona, zodiacal light, gegenschein, comets, origin of cometary and meteoric material in space, the emission of gaseous nebulæ, the peculiar changes observed in the nebula surrounding *Nova Persei*, the northern lights, the variations in atmospheric electricity and terrestrial magnetism and in the barometric pressure. Schwarzschild[2] computed from radiation pressure on small spherical conductors the size of bodies of unit density for which the ratio of radiation pressure to gravitational attraction would be a maximum.

Before the Congrès international de Physique in 1900, Professor Lebedew,[3] of the University of Moscow, described an arrangement of apparatus which he was using at that time for the measurement of light pressure. He summarizes the results already obtained as follows:

> Les résultats des mesures que j'ai faites jusqu'ici peuvent se résumer ainsi: L'expérience montre qu'un faisceau lumineux incident exerce sur les surfaces planes absorbantes et réfléchissantes des pressions qui, aux erreurs près d'observation, sont égales aux valeurs calculées par Maxwell et Bartoli.

No estimate of the "errors of observation" was given in the paper, nor other numerical data. Unfortunately the proceedings of the Paris Congress did not reach the writers, nor any intimation of the methods or results of Professor Lebedew's work, until after the publication of their own preliminary experiments.

The writers[4] presented the results they had obtained by

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[1] S. A. ARRHENIUS, *Lehrbuch der kosmischen Physik*, Leipzig, 1903, pp. 149–58, 200–208, 226, 920–5.

[2] K. SCHWARZSCHILD, *Kgl. bayer. Akademie d. Wissenschaften*, 31, 293, 1901.

[3] P. LEBEDEW, *Rapports présentés au Congrès international de Physique* (2), p. 133. Paris, 1900.

[4] E. F. NICHOLS and G. F. HULL, *Science*, 14, 588 (October 18, 1901); *Phys. Rev.*, 13, 293 (November, 1901); ASTROPHYSICAL JOURNAL, 15, p. 62 (January, 1902).

measurements of radiation pressure at eight different gas pressures, in a preliminary communication to the American Physical Society, meeting with Section B of the American Association at Denver, August 29, 1901. The main arguments underlying the method of measurement of the radiation pressure may here be given.

In the experiments of earlier investigators every approach to the experimental solution of the problem of radiation pressure had been balked by the disturbing action of the gases which it is impossible to remove entirely from the space surrounding the body upon which the radiation falls. The forces of attraction or repulsion, due to the action of gas molecules, are functions, first, of the temperature difference between the body and its surroundings, caused by the absorption by the body of a portion of the rays which fall upon it; and, second, of the pressure of the gas surrounding the illuminated body. In the particular form of apparatus used in the present study, the latter function appears very complicated, and certain peculiarities of the gas action remain inexplicable upon the basis of any simple group of assumptions which the writers have so far been able to make.

Since we can neither do away entirely with the gas nor calculate its effect under varying conditions, the only hopeful approach which remains is to devise apparatus and methods of observation which will reduce the errors due to gas action to a minimum. The following considerations led to a method by which the elimination of the gas action was practically accomplished in the present experiments:

1. The surfaces which receive the radiation, the pressure of which is to be measured, should be as perfect reflectors as possible. This will reduce the gas action by making the rise of temperature due to absorption small, while the radiation pressure will be increased; the theory requiring that a beam, totally reflected, shall exert twice the pressure of an equal beam, completely absorbed.

2. By studying the action of a beam of constant intensity upon the same surface surrounded by air at different pressures,

certain pressures may be found where the gas action is less than at others.

3. The apparatus — some sort of torsion balance — should carry two surfaces symmetrically placed with reference to the rotation axis, and the surfaces of the two arms should be as nearly equal as possible in every respect. The surfaces or vanes should be so constructed that if the forces due to gas action (whether suction or pressure on the warmer surface) and radiation pressure have the same sign in one case, a reversal of the suspension should reverse the gas action and bring the two forces into opposition. In this way a mean of the forces on the two faces of the suspension should be, in part at least, free from gas action.

4. Radiation pressure, from its nature, must reach its maximum value instantly, while observation has shown that gas action begins at zero and increases with length of exposure, rising rapidly at first, then more slowly to its maximum effect, which, in many of the cases observed, was not reached until the exposure had lasted from two and a half to three minutes. For large gas pressures an even longer exposure was necessary to reach stationary conditions. The gas action may be thus still further reduced by a ballistic or semi-ballistic method of measurement.

Ballistic observations of radiation pressure were made at air pressures ranging from 96.3 mm to 0.06 mm of mercury. The average radiation pressure of the standard beam was found to be 1.05×10^{-4} dyne, with a probable error of 6 per cent. To compare this value of the pressure with the theoretical value as given by the Maxwell-Bartoli formula, $p = \frac{E(1+\rho)}{V}$, it was necessary to measure E, the energy of the beam. This was done by a bolometric method in which the measurement of the energy was made to depend upon the resistance of the bolometer strip. Using the value of the energy thus obtained and 0.92[1] as the reflection coefficient of the silver surfaces, it was found that the

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[1] This value was obtained from the measurements of Langley, Rubens, Nichols, and Paschen for the assumed mean wave-length of the beam.

pressure directly observed was about 20 per cent. lower than that computed from the Maxwell-Bartoli formula. After the publication of the paper it was found that an error had been made in the measurement of the resistance of the bolometer strip, owing to a fault in its construction. A new estimation of the resistance gave an energy value which brought the theoretical value of the pressure very close to that found by direct measurement. But another method of measuring the energy was adopted in the later experiments described in this paper.

In the number of the *Annalen der Physik* for November, 1901, Professor Lebedew[1] published the results of a more varied series of measurements of radiation pressure than the early measurements of the present writers. The principal difference between the methods employed by him and by the writers for determining the pressure was that he used very thin metallic vanes surrounded by gas at extremely low pressures, thus following Maxwell's suggestion literally, while the writers used silvered glass vanes and worked at large gas pressures for which the gas action had been carefully and exhaustively studied and found to be negligibly small for short exposures. From our knowledge of the variation of gas action in different vacua, we feel sure that our method would not have been successful in high vacua because of the relatively large gas action. Professor Lebedew's own results, with blackened vanes of lower heat conductivity, show that his success in eliminating gas disturbance was due to the high heat conductivity of thin vanes rather than to the high vacua employed.

Professor Lebedew's[2] estimate of the accuracy of his work is such as to admit of possible errors of 20 per cent. in his final results. An analysis of Professor Lebedew's paper and comparison with our preliminary experiments seem to show that his accidental errors were larger than ours, but through the undiscovered false resistance in the bolometer our final results were somewhat farther from the theory than his. Either of the above researches would have been sufficient to establish the *existence*

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[1] P. LEBEDEW, *Ann. der Phys.*, **6**, 433, 1901.

[2] P. LEBEDEW, *Ann. der Phys.*, **6**, 457, 1901.

of a pressure due to radiation, but neither research offered, in our judgment, a satisfactory *quantitative* confirmation of the Maxwell-Bartoli theory.

LATER PRESSURE MEASUREMENTS.

Description of apparatus: the torsion balance.—The form of suspension of the torsion balance, used to measure radiation pressure in the present study, is seen in Fig. 1. The rotation axis *a b* was a fine rod of drawn glass. A drawn-glass cross-arm *c*, bent down at either end into a small hook, was attached to the axis. The surfaces *C* and *D*, which received the light beam, were circular microscope cover-glasses, 12.8 mm in diameter and 0.17 mm thick, weighing approximately 51 mg each. To distinguish the two vanes from each other, in case individual differences should appear in the measurements, and also to mark the two faces of each vane for subsequent recognition, a letter *C* was marked on one, and *D* on the other, by diamond scratches. Through each glass a hole 0.5 mm or less in diameter was drilled near the edge, by means of which the glasses could be hung on the hooks on the cross-arm *c*. On opposite sides of the rotation axis at *d* two other drawn-glass cross-arms were attached. The cover-glasses slipped easily between these, and were thus held securely in one plane. Farther down on *a b*, a small silvered plane mirror m_1 was made fast at right angles to the plane of *C* and *D*. This mirror was polished bright on the silver side, so that the scale at S_s (Fig. 2) could be read in either face. A small brass weight m_3 (Fig. 1), of 452 mg mass and of known dimensions, was attached at the lower end of *a b*. The cover-glasses which served as vanes were silvered and brilliantly polished on the silvered sides, and so hung on the small hooks that both silver faces or both glass faces were presented to the light. A quartz fiber f_2, 3 cm long, was made fast to the upper end of *a b*, and to the lower end of a fine glass rod d_1 which carried a horizontal magnet m_2. The rod d_1 was in turn suspended by a short fiber to a steel pin *e*, which could be raised or lowered in the bearing *h*. The whole was carried by a bent glass tube *t*, firmly fastened to a solid brass foot *F*, resting on a plane ground-glass plate *P*, cemented to a brass platform mounted on three leveling screws not shown. A bell-jar *B*, 25 cm high and 11 cm in diameter, covered the balance. The flange of the bell-jar was ground to fit the plate *P*. A ground-in hollow glass stopper fitted the neck of the bell-jar, which could thus be put in

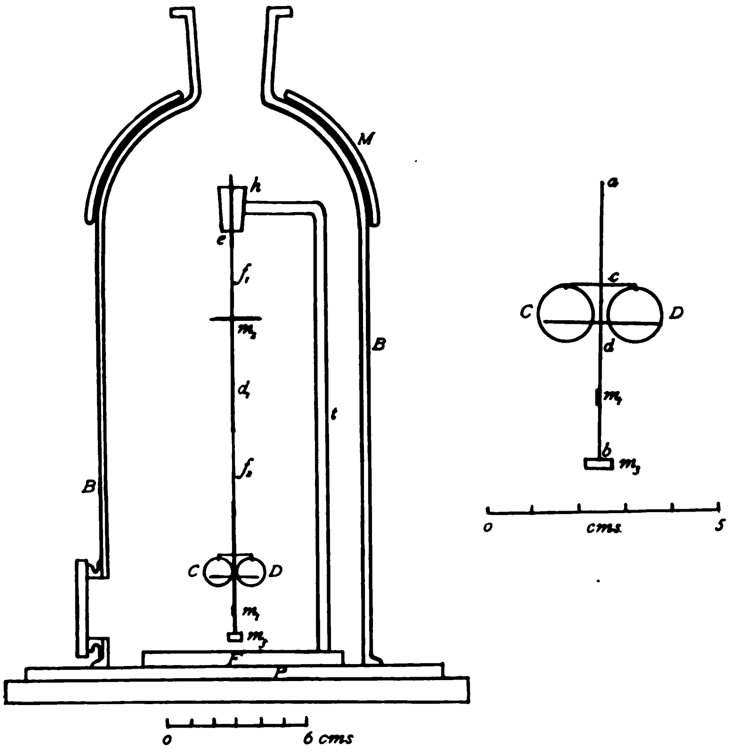

FIG. 1.

connection with a system of glass tubes leading to a Geissler mercury pump, a MacLeod pressure gauge, and a vertical glass tube dipping into a mercury cup and serving as a rough manometer for measuring the larger gas pressures employed during the observations. The low pressures were measured on the MacLeod gauge in the usual way. A semicircular magnet *M*, fitted to the vertical curvature of the bell-jar, was used to direct the suspended magnet m_2 and thus to control the zero position of the torsion balance. By turning *M* through 180°, the opposite faces of the vanes *C* and *D* could be presented to the light.

THE ARRANGEMENT OF APPARATUS.

A horizontal section of the apparatus through the axis of the light beam is shown in Fig. 2. The white-hot end of the horizontal carbon S_1, of an A. T. Thompson 90° arc-lamp, fed by alternating current, served as a source. The arc played against the end of the horizontal carbon from the vertical carbon which was screened from the lenses L_1 and L_2 by an asbestos diaphragm d_2. A lens, not shown, projected an enlarged image of the arc and carbons on an adjacent wall, so that the position of the carbons and the condition of the arc could be seen at all times by both observers.

The cone of rays passing through the small diaphragm d_2 fell upon the glass condensing lenses L_1, L_2. At d_3 a diaphragm, 11.25 mm in diameter, was interposed, which permitted only the central portion of the cone of rays to pass. Just beyond d_3, the beam passed to a shutter at S_2. This shutter was worked by a magnetic escapement, operated by the seconds contact of a standard clock. The observer at T_1 might choose the second for opening or closing the shutter, but the shutter's motion always took place at the time of the second's contact in the clock. Any exposure was thus of some whole number of seconds' duration. The opening in the shutter was such as to let through, at the time of exposure, all of the direct beam which passed through d_3, but to shut out stray light. Just beyond the shutter and attached to the diaphragm d_5 was a 45° glass plate which reflected a part of the beam to the lens L_5, by means of which an image of d_3 was projected upon one arm of a bolometer at *R*. The glass lens L_3 focused a sharp image of the aperture d_3 in the plane of the vanes of the torsion balance B_1, under the bell-jar. The bell-jar was provided with three plate-glass windows W_1, W_2, W_3. The first two gave a circular opening 42 mm in diameter, and through the third, deflections of the balance were read by a telescope and scale. The lens L_3 was arranged to move horizontally between the stops S_3 and S_4. These were so adjusted that when the lens was against S_3 the sharp image of the aperture d_3 fell centrally upon one vane; and when against S_4 the image fell centrally upon the other. This adjustment, which was a very important one, was made by the aid of a telescope T_2, mounted on the carriage of a dividing engine. This was used to observe and measure the position of the rotation axis, as well as the positions of the images of d_3, when the lens L_3 was against the stops. For the latter measurements the vanes could be moved out of the way by turning the suspension through 90° by the control magnet *M* (Fig. 1).

To make sure that the balance as used was entirely free from any magnetic moment or disturbance, the small magnet m_2 was clamped in one position to maintain a constant zero, and the period of the balance was accurately measured with the axis of the large magnet *M* in the vertical plane of the vanes and again when the axis was at right angles to the plane of the vanes. Several series of this sort failed to show a difference of 0.1 second in the period of the balance for the two positions of the magnet.

The bolometer at *R* (Fig. 2) was of sheet platinum 0.001 mm thick, rolled in silver. The strip was cut out in the form shown

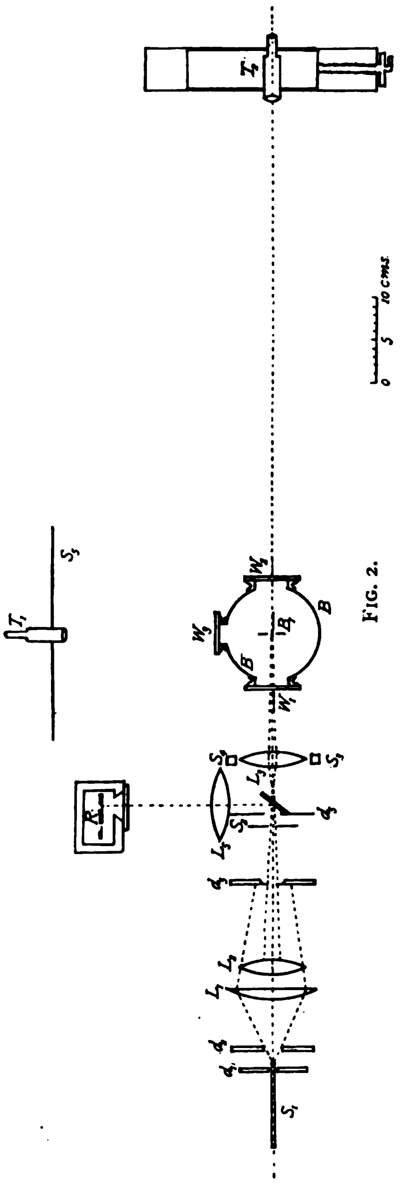

FIG. 2.

in Fig. 3, and mounted on a thin sheet of slate *S*. Two windows had been cut in the slate behind the strips at *ABCD* where the silver had been removed leaving the thin platinum. The platinum surfaces were blackened by Kurlbaum's process. The image from L_5 (Fig. 2), fell at *D*. The silver ends between *A* and *C* were connected with *E* and *F* respectively. On the heavy wire *EF* a sliding contact *c* served to balance the bridge, all four arms of which are shown in the figure.

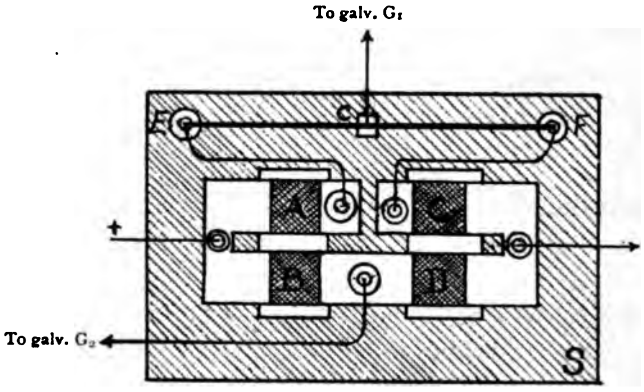

FIG. 3.

METHODS OF OBSERVATION.

The observations leading to the results given later were of three different kinds: (1) the calibration of the torsion balance; (2) the measurement of the pressure of radiation in terms of the constant of the balance; and (3) the measurement of the energy of the same beam in erg-seconds by the rate of temperature rise of a blackened silver disk, of known mass and specific heat.

1. The determination of the constant of the torsion balance was made by removing the vanes *C* and *D* and accurately measuring the period of vibration. Its moment of inertia was easily computed from the masses and distribution of the various parts about the axis of rotation. The moment of torsion for 1 mm deflection on a scale 105 cm distant was 0.363×10^{-5} dyne × cm. This value divided by one-half the distance between the centers

of the light spots on the two vanes gave the force in dynes per scale division deflection. As the light spots were circles 11.25 mm in diameter the area of the image was very nearly 1 sq. cm, hence the above procedure gave roughly the pressure in dynes per square centimeter.

2. In the measurements of radiation pressure, it was easier to refer the intensity of the beam at each exposure to some arbitrary standard which could be kept constant than to try to hold the lamp as steady as would otherwise have been necessary. For this purpose, the bolometer at *R* (Fig. 2) was introduced, and simultaneous observations were made of the relative intensity of the reflected beam by the deflection of the galvanometer G_2, and the pressure due to the transmitted beam by the deflection of the torsion balance. The actual deflection of the balance was then reduced to a deflection corresponding to a galvanometer deflection of 100 scale divisions. The galvanometer sensitiveness was carefully tested at the beginning and end of each evening's work. All observations of pressure were thus reduced to the pressure due to a beam of fixed intensity.

At each series of radiation pressure measurements, two sets of observations were made. In one of these sets, static conditions were observed, and in the other, the deflections of the balance due to short exposures were measured. In the static observations, each vane of the balance was exposed in turn to the beam from the lamp, the exposures lasting until the turning points of the swings showed that stationary conditions had been reached. The moment of pressure of radiation and gas action combined would thus be equal to the product of the static deflection and the constant of the balance. The torsion system was then turned through 180° by rotating the outside magnet, and similar observations were made on the reverse side of the vanes. All turning-points of the swinging balance in these observations were recorded. From the data thus obtained the resultant of the combined radiation and gas forces could be determined for the time of every turning-point. Every value was divided by the deflection at standard sensitiveness of the galvanometer G_2 read at the same time and was thus reduced to standard lamp.

Results thus obtained, together with the ballistic measurements, showed the direction and extent of the gas action as well as its variation with length of exposure.

The reasons for reversing the suspension follow: The beam from the lamp, before reaching the balance, passed through three thick glass lenses and two glass plates. All wave-lengths destructively absorbed by the glass were thus sifted out of the beam by the time it reached the balance vanes. The silver coatings on the vanes absorbed therefore more than the glass. The radiation pressure was always away from the source, irrespective of the way the vanes were turned, while the gas action would be exerted mainly on the silvered sides of the vanes.

At the close of the pressure and energy measurements, when the reflecting power of the silver faces of the vanes was compared with that of the glass-silver faces, the reflection from the silver faces was found very much higher than that for the glass faces backed by silver. This result was the more surprising because the absorption of the unsilvered vanes was found by measurement to be negligibly small.[1] This unexpected difference in reflecting power of the two faces of the mirrors prevented the elimination of the gas action, by the method described, from being as complete as had been hoped for. But by choosing a gas pressure where the gas action after long exposure is small, the whole gas effect during the time of a ballistic exposure may be so reduced as to be of little consequence in any case.

By exposing each of the vanes in turn and by reversing the suspension and averaging results, nearly all errors due to lack of symmetry in the balance or in the position of the light images with reference to the rotation axis, or errors due to lack of uniformity in the distribution of intensity in different parts of the image, could be eliminated.

The changing character of the gas action, both with time of exposure and gas pressure surrounding the balance vanes, is well illustrated in eight series of static observations in which the

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[1] LORD RAYLEIGH records a similar difference between the reflection from air-silver and glass-silver surfaces. *Scientific Papers*, Cambridge, 2, 538–539, 1900.

glass faces of both vanes were exposed.[1] The results obtained on the two vanes were averaged and plotted as curves in Fig. 5,

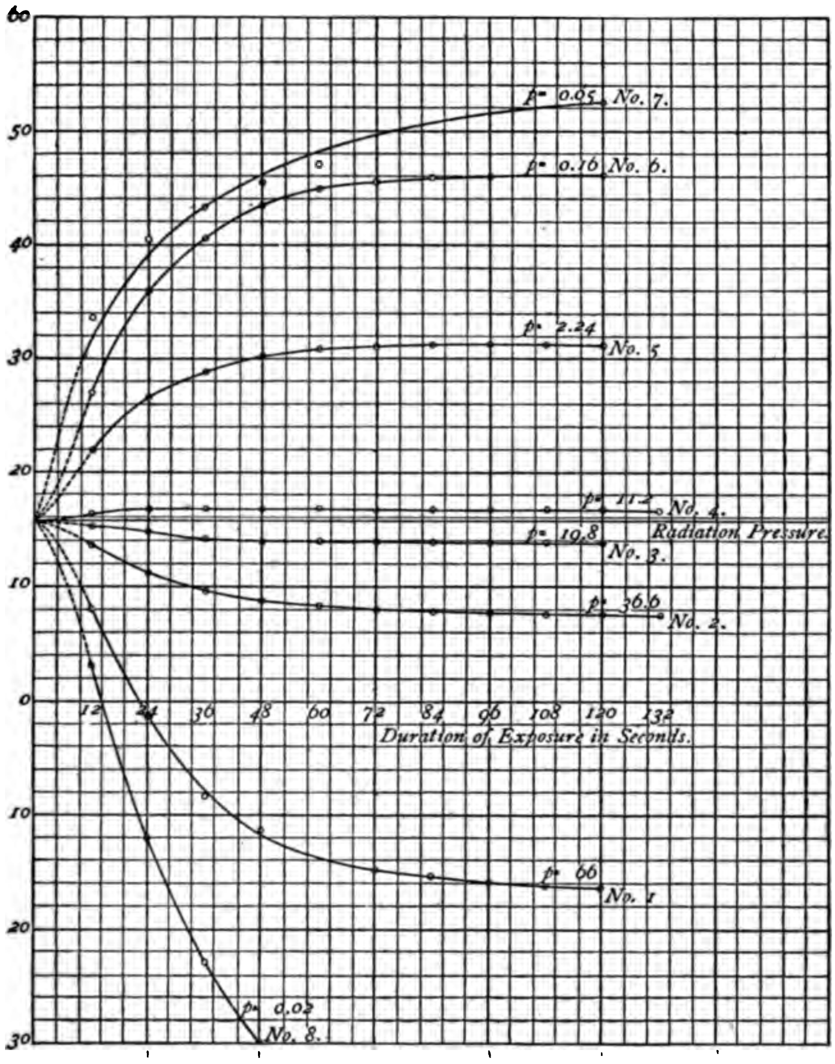

FIG. 4.

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[1] Observations were also made on the silver faces, but the gas action when the glass faces were exposed was nearly double that for the silver faces, so the least favorable case is shown.

where static deflections due to combined radiation pressure and gas action are shown as ordinates and duration of exposure, in seconds, as abscissæ.[1] A horizontal line through the diagram gives the mean value of the moment of radiation pressure computed from the data in Table I. Decrease of the deflection with time indicates gas repulsion on the warmed silver faces and increase in deflection, gas suction. It will be seen from the curves that beginning at a gas pressure of 66 mm of mercury, the gas action was repulsion changing to suction in passing from 19.8 to 11.2 mm. In the last two cases the total gas action is small. For lower pressures the suction increases to 0.05 mm. At a gas pressure of 0.02 mm the gas action is again a strong repulsion.

The curves indicate the existence of two gas pressures, at which the gas action in our arrangement of apparatus should be zero, one between 19.8 and 11.2 mm and the other between 0.05 and 0.02 mm.[2] The former region was chosen for the ballistic measurements and nearly all of the observations were made at a gas pressure of approximately 16 mm. Even for the two pressures where the decrease in the static deflection was most rapid, *i. e.*, at gas pressures of 66 and 0.02 mm, the first throw was always in the direction of radiation pressure. The gas action is strongly influenced by very slight changes in the inclination of the plane of the vanes to the vertical and also by any object introduced under the bell-jar anywhere near the vanes. For instance, a very considerable effect was observed when a small vessel of phosphoric anhydride was placed under the jar behind the vanes, though the nearest wall of the vessel was separated from the vanes by a distance of at least 3 cm.

During the observations, the polished silver coatings on the vanes deteriorated rapidly; new coatings rarely lasted for more than two evenings' work. As the balance had to be removed

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[1] Ordinates of the curves are proportional to moments.

[2] Crookes in his work with the radiometer discovered certain gas pressures for which the combined gas and radiation forces neutralized, but as he did not discriminate between forces due to radiation and gas forces his results were apparently capricious and his reasoning somewhat confused. See *Phil. Trans.*, p. 519, 1875.

and the mirrors taken from the hooks, silvered, polished, and replaced a great number of times during the entire series of measurements, although great care was taken in setting the plane of the vanes vertical, it is not likely that precisely the same conditions for gas action were ever repeated. The principal value of the static results was in indicating favorable gas pressures for work, rather than affording quantitative estimates of the gas action in short exposures. The dotted parts of the curves are not based on results of observation and might perhaps have been omitted without loss.

It was plain, therefore, that further elimination of the gas action must be sought in exposures so short that the gas action would not have time to reach more than a small fraction of its stationary value. This led to the method of ballistic observations.

THE BALLISTIC OBSERVATIONS.

In passing from the static to the ballistic observations it must always be possible to compute the static equivalent of the ballistic swings. Furthermore the exposures should be made as short as possible without reducing the size of the swing below a value which can be accurately measured.

If the exposure lasts for one-half the period of the balance, the deflection, if the gas action be small, and the damping zero, is equal to 2θ where θ is the angle at which the torsion of the fiber will balance the moment produced by the radiation pressure. If the duration of the exposure be one-quarter of the period of the balance, the angle of deflection is $\theta\sqrt{2}$. The deflection is thus reduced by 30 per cent., but the effect of the gas action is reduced in greater proportion. It was decided, therefore, to expose for six seconds, one-quarter of the balance period. Neglecting the gas action, the equation[1] of motion of the balance is given by

$$\kappa\frac{\partial^2\theta}{\partial t^2} + 2\epsilon\frac{\partial\theta}{\partial t} = -G\theta + L\ ,$$

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[1] We are justified in using quantitatively this equation, containing a damping term proportional to the velocity, because the amplitudes of the successive swings of the torsion balance, when no energy fell upon the vanes, were found experimentally to follow accurately the exponential law.

where κ = the moment of inertia of the torsion balance,
ϵ = the damping constant,
G = the moment of torsion of the fiber for $\theta = 1$ radian,
and L = the moment of the radiation force.

The solution of this equation is

$$\theta = \frac{L}{G}\left\{ 1 - e^{-\frac{\epsilon}{\kappa}t} \cos\sqrt{\frac{G}{\kappa} - \frac{\epsilon^2}{\kappa^2}}\,t \right\},$$

$$= \frac{L}{G}\left\{ 1 - e^{-\frac{\epsilon}{\kappa}t} \cos 2\pi\frac{t}{T} \right\}, \tag{1}$$

the constants of integration having been determined from the condition that

$$\theta = \frac{\partial\theta}{\partial t} = 0 \text{ when } t = 0 \ .$$

When

$$t = \frac{T}{4},\ \theta = \frac{L}{G} \text{ and } \frac{\partial\theta}{\partial t} = \frac{L}{G}\left(\frac{\epsilon}{\kappa}e^{-\frac{\epsilon}{\kappa}t} \cos 2\pi\frac{t}{T} + e^{-\frac{\epsilon}{\kappa}t}\frac{2\pi}{T} \sin 2\pi\frac{t}{T}\right). \tag{2}$$

The light being cut off when $t = \frac{T}{4}$, the equation of motion becomes

$$\kappa\frac{\partial^2\theta}{\partial t^2} + 2\epsilon\frac{\partial\theta}{\partial t} = -G\theta\ , \tag{3}$$

the solution of which is $\theta = Ae^{-\frac{\epsilon}{\kappa}t}\cos\left(2\pi\frac{t}{T} + \alpha\right)$, where A and α can be determined by the conditions imposed by equation (2). Neglecting very small quantities, the value of the amplitude A is expressed by the equation

$$A = \frac{L}{G}\left\{ 1 + r + \frac{2}{\pi}r^{\frac{1}{2}} \log\left(\frac{1}{r}\right) \right\}^{\frac{1}{2}}, \tag{4}$$

where r is the ratio of successive amplitudes of the damped vibrations. If $r = 1$, that is, if the motion is undamped, $A = \frac{L}{G}\sqrt{2}$. In the partial vacuum used in the experiments (16 mm of mercury, a value chosen from the curves in Fig. 4), r was found to be equal to 0.783; consequently $A = 1.357\frac{L}{G}$. (5)

From this it is seen that the total angle of deflection of the torsion balance in the ballistic measurements is equal to 1.357 times the angle at which the moment of the torsion of the fiber balances the moment of the radiation pressure.

The duration of exposure was always six seconds without appreciable error, but the period of the balance on account of slight accidental shifting of small additional masses upon the counterpoise weight m_3 (Fig. 1), differed from twenty-four seconds sometimes by 1 per cent. It is necessary, therefore, to find the error in the deflection due to this variation in the period. This is done by making $t = \frac{T}{4} + \delta$ in equation (2) and in introducing the new conditions in equation (3). But it is simpler and sufficiently accurate to assume the motion as undamped. For this condition the amplitude

$$A = \frac{L}{G}\left\{2 + 2\sin 2\pi\frac{\delta}{T}\right\}^{\frac{1}{2}} = \sqrt{2}\,\frac{L}{G}\left(1 + \pi\frac{\delta}{T}\right) \text{ nearly.}$$

For $T = 23.75$ seconds, $\frac{T}{4} = 5.94$ and $\delta = 0.06$. Hence

$$A = \sqrt{2}\,\frac{L}{G}(1.008).$$

If $\delta = 0$, $A = \sqrt{2}\,\frac{L}{G}$, consequently an error of 1 per cent. in T causes an error of 0.8 per cent. in A.

To make sure that the observed radiation pressures depended only on the intensity of the beam, and were uninfluenced by the wave-length of the incident energy, the ballistic observations of pressure, the thermal measurements of intensity, and the determination of the reflection coefficients, were carried out for three entirely different wave-groups of the incident radiation. In the measurements designated "through air," no absorbing medium was introduced in the path of the beam between the lamp and the balance except the glass lenses and plates already mentioned. In the measurements "through red glass," a plate of ruby glass was put in the path of the beam between L_2 and d_3 (Fig. 2). For the observations "through water cell," a 9 mm layer of distilled water in a glass cell was placed in the path of the beam at the same point.

The separate observations entering into a single series of ballistic measurements and their treatment will appear from Table II, which is copied direct from the laboratory notebook and represents an average ballistic series. The designations

EVC_s, WVD_s, EVD_g, WVC_g mean that the vane C in the first case was on the east side of the rotation axis with its silver face toward the light. The subscript g signifies that the glass face of the vane was toward the light. The second column of the table gives the zero reading of the balance before opening the shutter; the third, the end of the swing produced by a six-second exposure; the fourth, the deflection of the balance; the fifth, the ballistic deflection of the lamp galvanometer G_2. Columns six and seven give the balance deflection reduced to standard lamp.

The results of all the ballistic pressure measurements "through air" are collected in Table II. In the fourth and fifth columns two values are given for the constant of the lamp galvanometer G_2, since reversing the magnet on the balance bell-jar to reverse the suspension within affected the constant of the galvanometer slightly, the values for the silver and glass faces forward were never the same. The subscripts show to which series, silver or glass, the constant belongs. The values of the lever-arm l of the balance, in the sixth column, are obtained by measuring the distance between the centers of the images when on the east and west vanes (by the dividing engine T_2, Fig. 2) and dividing by two. The columns headed $\frac{C_s + D_s}{2} = P_s$ and $\frac{C_g + D_g}{2} = P_g$ are the average moments due to pressures for the silver and glass sides of the vanes respectively toward the light. The next two columns contain these moments corrected for a period of 24 seconds of the torsion balance. The columns headed $\frac{P_s \times G_s}{l}$ and $\frac{P_g \times G_g}{l}$ are the corresponding forces reduced to standard sensitiveness, $G = 1000$. The final column contains the averages of the two columns which precede it. Table III exhibits corresponding data for "red glass" and "water cell." The air pressure, period of the balance, lever arm and galvanometer constants are those given in Table II for the same date.

In these ballistic measurements the lamp reading was the throw due to an exposure of the light upon the bolometer for six seconds, but in the energy measurements the lamp reading was a stationary deflection due to prolonged exposure. To bring the pressure values into comparison with the energy meas-

TABLE I.

AUGUST 28. LIGHT PRESSURE. BALLISTIC MEASUREMENTS. AIR.

Surface	Zero	Throw	Deflection	Lamp	Deflection (Lamp 100)	
					E. V.	W. V.
			mm	mm	mm	mm
E V C_s....	281.4	248.5	32.9	164.3	20.0	
W V D_s...	281.5	313.9	32.4	164.5		19.7
E V C_s....	281.4	249.8	31.6	157.9	20.0	
W V D_s...	281.5	310.5	29.0	147.0		19.8
E V C_s....	281.5	252.6	28.9	144.8	20.0	
W V D_s...	281.5	309.6	28.1	141.8		19.8
E V C_s....	281.5	252.9	28.6	143.5	19.9	
W V D_s...	281.5	309.3	27.8	140.4		19.8

Average......19.97 19.77

Average, $\frac{C_s + D_s}{2} = 19.87$

MAGNET REVERSED.

Surface	Zero	Throw	Deflection	Lamp	E. V.	W. V.
E V D_g....	280.1	246.0	34.1	180.4	18.92	
W V C_g...	280.0	317.8	37.8	187.3		20.20
E V D_g....	279.8	247.2	32.6	170.8	19.20	
W V C_g....	279.4	313.7	34.3	169.4		20.25
E V D_g....	279.1	248.9	30.2	161.1	18.80	
W V C_g....	279.0	311.9	32.9	161.6		20.35
E V D_g....	279.0	249.1	30.0	158.9	18.90	
W V C_g...	278.9	311.2	33.2	164.4		20.20

Average.....18.97 20.25

Average, $\frac{C_g + D_g}{2} = 19.61$

TABLE II.

RADIATION PRESSURE. BALLISTIC MEASUREMENTS, THROUGH AIR.

Date	Air Pressure in mm of Hg.	Balance Period T	Sens. of Galvanometer		l=Lever Arm cm	$\frac{C_s + D_s}{2} = P_s$	$\frac{C_g \times D_g}{2} = P_g$	P_s corrected for $T = 24^\circ$	P_g corrected for $T = 24^\circ$	$\frac{P_s \times G_s}{l}$	$\frac{P_g \times G_g}{l}$	Average
			G_s (Silver)	G_g (Glass)								
June 19..............	32.5	23.75	[734]		0.814	Aver.=	18.88	Aver.=	18.73	Aver.=	16.89	16.89
20..............	32.5	23.75	756.•	768	0.814	19.67	16.94	19.51	16.81	18.12	15.86	17.00
23..............	37.0	23.75	700	716	0.814							
July 23..............	16.0	23.75	682	707	0.831	21.16	20.42	21.00	20.26	17.25	17.25	17.25
25..............	16.6	23.75	684	684	0.815							
26..............	16.6	23.75	720	710	0.815	19.34	19.98	19.18	19.82	16.93	17.28	17.10
August 27..............	16.8	23.82	724	710	0.823	20.16	19.40	20.00	19.25	17.60	16.61	17.10
28..............	15.7	23.82	721	716	0.824	19.87	19.61	19.73	19.48	17.26	16.97	17.10
29..............	13.7	23.82	712	701	0.824	19.68	20.07	19.53	19.92	16.90	16.97	16.94
31..............	14.0	24.00	718	713	0.810	18.55	18.94	18.55	18.94	16.44	16.60	16.52
September 1..........	16.6	24.00	692	672	0.808	19.14	20.17	19.14	20.17	16.40	16.78	16.59
20..........	16.4	23.78	670	676	0.812	20.96	20.02	20.81	19.87	17.17	16.54	16.86
23..........	16.4	23.78	666	684	0.816	21.32	20.27	21.16	20.12	17.27	16.87	17.07
24..........	16.2	23.78	667	669	0.816	20.76	19.80	20.60	19.65	16.84	16.11	16.47

Average......17.11 16.71 16.91 ± 0.053

urements it is necessary to reduce the average of the quantities in the last column to pressures in dynes by multiplying by 0.363×10^{-5}, the torsion coefficient of the quartz fiber, and to reduce not only to a static deflection of the torsion balance but also to a static deflection of the lamp galvanometer G_s. The ratio of a ballistic to a static deflection of the galvanometer G_s was obtained from a long series of lamp exposures. This ratio was found "through air" to be $= 1.55$; "through red glass" $= 1.535$; "through water cell" $= 1.502$. These differences are probably due not solely to the damping constant of the galvanometer but to the peculiar manner in which the bolometer was warmed up to its stationary conditions by the beam from the lamp. Applying these reduction factors to the averages in Tables II and III, we obtain the following results. The pressure of the standard light beam which has passed

(*a*) through air $= 16.91 \times \dfrac{1.55}{1.357} \times 0.363 \times 10^{-5} =$

$(7.01 \pm 0.023) \times 10^{-5}$ dynes ;

(*b*) through red glass $= 16.91 \times \dfrac{1.535}{1.357} \times 0.363 \times 10^{-5} =$

$(6.94 \pm 0.024) \times 10^{-5}$ dynes ;

(*c*) through water cell $= 16.20 \times \dfrac{1.502}{1.357} \times 0.363 \times 10^{-5} =$

$(6.52 \pm 0.028) \times 10^{-5}$ dynes .

TABLE III.

RADIATION PRESSURE. BALLISTIC MEASUREMENTS.

THROUGH WATER CELL.

Date	$\frac{C_s + D_s}{2}$	$\frac{C_g + D_g}{2}$	P_s corrected for $T=24°$	P_g corrected for $T=24°$	$\frac{P_s \times G_s}{l}$	$\frac{P_g \times G_g}{l}$	P Average
June 20	18.62	17.10	18.46	16.96	17.14	16.00	16.57
July 25	19.00	20.10	18.85	19.94	15.82	16.74	16.28
26	18.03	19.39	17.89	19.33	15.80	16.84	16.32
August 27	18.63	18.66	18.50	18.53	16.29	15.99	16.14
29	18.25	19.02	18.10	18.87	15.68	16.06	15.87
September 20	20.39	19.14	20.23	19.00	16.69	15.82	16.25
23	20.21	19.51	20.05	19.36	16.37	16.23	16.30
24	19.84	18.91	19.69	18.77	16.10	15.40	15.70
Average	.....	.....	.....	.....	16.24	16.15	16.20 ±0.066

TABLE III—*Continued.*

THROUGH RED GLASS.

June 23	19.99	18.40	19.83	18.26	17.05	16.06	16.56
July 25	20.70	20.94	20.54	20.77	17.24	17.43	17.33
August 27	19.97	19.25	19.82	19.10	17.46	16.46	16.96
28	19.99	19.42	19.84	19.28	17.36	16.75	17.05
29	19.99	19.92	19.84	19.77	17.14	16.82	16.98
31	18.98	19.14	18.98	19.14	16.82	16.84	16.83
September 20	21.00	19.97	20.83	19.82	17.19	16.50	16.84
23	21.48	20.34	21.31	20.18	17.39	16.92	17.15
24	21.00	19.68	20.83	19.53	17.03	16.03	16.53
Average	.....	.....	.....	.....	17.18	16.65	16.91 ±0.051

THE ENERGY MEASUREMENTS.

Before rejecting the bolometer method used in the preliminary measurement of energy, a second bolometer of slightly different construction was tried; but the lack of uniformity of resistance, already mentioned, made its indications too uncertain for the present work. The radiant intensity of the beam used in the later experiments was determined by directing it upon the blackened face of a silver disk, weighing 4.80 grams of 13.3 mm diameter and of 3.58 mm thickness, and by measuring its rate of temperature rise as it passed through the temperature of its surroundings. The disk was obtained from Messrs. Tiffany & Co., and was said by them to be 99.8 per cent. fine silver. Two holes were bored through parallel diameters of the disk, one-fourth of the thickness of the disk from either face. Two iron-constantan thermo-junctions, made by soldering 0.1 mm wires of the two metals, were drawn through the holes into the center of the disk. To insulate the wires from the disk, fine drawn glass tubes were slipped over them and thrust into the holes, leaving less than 2 mm bare wire on either side of the junctions. The wires were sealed into the tubes, and the tubes into the disk by solid shellac. The tubes projected 15 mm or more from the disk and were bent upward in planes parallel to the faces of the disk. The general arrangement will be seen in Fig. 5. The disk was suspended by the four wires some distance below a small flat wooden box. On the box was fastened a calorimeter can swathed in cotton and filled with kerosene in which the constant thermo-junctions were immersed. Copper wires soldered to the two ends of the thermo-electric series were brought out of the calorimeter, and the circuit was closed through 1,000 ohms in series with the 500 ohms resistance of galvanometer G_1. The thermo-junctions in the disk were in series, and as each junction was midway between the central plane of the disk and either face, it was assumed that when the disk was slowly warmed by heating one face the electro-motive forces obtained corresponded to the mean temperature of the disk. One face of the disk was blackened by spraying it with powdered lampblack in alcohol containing a trace of shellac. This method was suggested by Professor G. E. Hale and gives very fine and uniform dead black coatings not inferior to good smoke deposits.

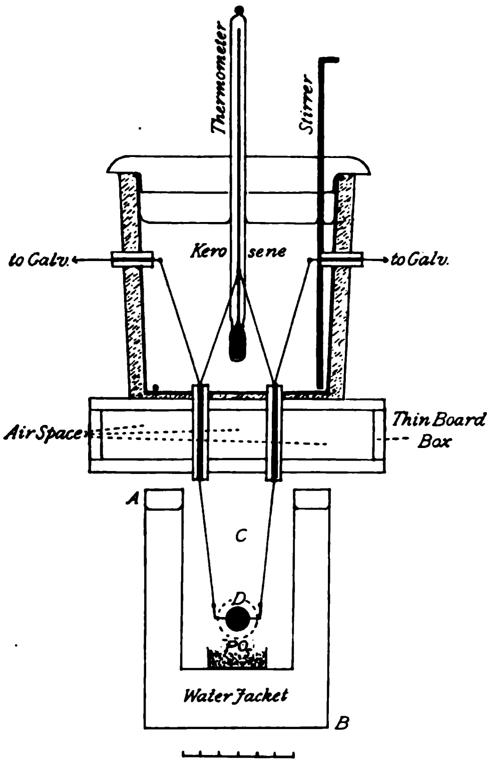

FIG. 5.

For the energy measurements the bell-jar and the torsion balance were removed from the platform P (Fig. 1) and a double-walled copper vessel, AB (Fig. 5), which served as a water jacket surrounding a small air chamber C, was mounted in the same place. A tube 2 cm in diameter was soldered into the front face of the jacket to admit the light beam into the chamber C. This opening was covered by a piece of plate glass similar to the plates forming the larger windows in the bell-jar.

The needle system in G_1, a four-coil du Bois-Rubens galvanometer, was suspended in a strong magnetic field so that its period was about four seconds. The system was heavily damped by a mica air-fan of large surface. The disk junctions and galvanometer responded quickly to the radiation, as was shown by the reversal of motion of the magnet system 1.2 seconds after the light was cut off from the disk, when the latter was a few degrees above the temperature of the room.

The disk was calibrated for temperature in terms of the deflection for a definite sensitiveness of the galvanometer G_1. For this purpose the disk was immersed in a kerosene bath and the galvanometer deflection measured for two different temperatures of the disk. One of these was about 18° C. above the comparatively steady temperature of the room, or calorimeter containing the standard temperature junctions (see Fig. 5), and the other about the same number of degrees below the room temperature. These two temperatures were measured by a Fuess Standard Thermometer divided into tenths of a degree and calibrated at the *Reichsanstalt*. Two calibrations of the silver disk were made some days apart. One of these series appears in full in Table IV. The first three columns of the table give the zero,

TABLE IV.

CALIBRATION OF SILVER DISK.

COLD BATH.

G_1 Readings			Disk T_1°	Room cal. T_2°	Deflection of G_1	Means of Alternate Deflections	G_1 Means	T_2-T_1°
Reversed	Zero	Direct						
	221.2							
	221.0	35.2	1°58	20°05	185.8			
	220.9							
402.0	*221.0*		1.60	20.07	181.0	185.7	183.4	18.47
	221.2							
	221.2	35.7	1.57	20.10	185.5	181.3	183.4	18.53
	221.2							
403.1	*221.5*		1.56	20.14	181.6	185.8	183.7	18.58
	221.9							
	222.0	35.9	1.54	20.16	186.1	182.2	184.1	18.62
	222.1							
405.0	*222.2*		1.52	20.20	182.8	186.3	184.5	18.68
	222.4							
	222.7	36.2	1.57	20.22	186.5	182.7	184.6	18.65
	223.0							
405.8	*223.1*		1.60	20.26	182:7	186.7	184.7	18.66
	223.2							
	223.3	36.3	1.59	20.30	187.0			
	223.5						184.0	18°60
	Correction to T_1 = 0°00.							

TABLE IV—*Continued.*

WARM BATH.								
	217.3							
	218.6	434.2	41°45	20°40	215.6			
	219.9							
2.0	*220.5*		41.35	20.42	218.5	213.7	216.1	20.93
	221.1							
	222.4	434.2	41.25	20.44	211.8	216.4	214.1	20.81
	223.7							
10.0	*224.4*		41.08	20.50	214.4	209.1	211.7	20.58
	225.1							
	225.7	432.1	40.90	20.55	206.4	212.4	209.4	20.35
	226.3							
16.3	*226.7*		40.80	20.60	210 4	204.8	207.6	20.20
	227.2							
	227.8	431.0	40.67	20.61	203.2	208.5	205.8	20.07
	228.4							
21.8	*228.5*		40.55	20.63	206.7	201.8	204.2	19.92
	228.7							
	229.0	429.4	40.43	20.65	200.4			
	229.3						209.8	20°41
	Correction to $T_1 = 0°10$.					Corrected, 20.51		

direct, and reversed reading of the galvanometer G_1. The fourth column gives the temperature of the bath in which the disk was immersed, and the fifth, that of the constant temperature calorimeter. The sixth column gives the deflections of G_1. The seventh column the means of the alternate deflections. The eighth, the mean of the two columns preceding it. The last column gives the difference in temperature between the two calorimeters in degrees C. For the total temperature range in the table, 39°11, the deflection of G_1 was 393.8 scale divisions for a sensitiveness of $G_1 = 996$. A range of one degree would thus give a deflection of 10.03 divisions for a sensitiveness of $G_1 = 1000$. The mean of two separate calibrations was 9.96 scale divisions for one degree temperature difference.

Before beginning a series of intensity measurements the disk was suspended in an air-chamber containing phosphoric anhydride and surrounded by a jacket of ice and salt. The disk was thus lowered to a temperature of about zero degrees and was then quickly transferred to the chamber *C* (Fig. 5), and the beam was directed upon it. When its temperature had risen to within five or six degrees of that of the chamber *C*, galvanometer readings were made at intervals of five seconds until the disk was heated to a temperature several degrees above its surroundings. The temperature of the chamber *C* was determined by removing the disk and cooling it to a point near the room temperature, then replacing it and observing its rate of temperature change for several minutes.

The notebook record of one series of observations showing the heating of the disk by the light beam is given in full in Table V. It will be seen from the table that the temperature of the disk passed that of the chamber thirty seconds after the beginning of the series. The readings of G_1 at equal time intervals on either side of the zero are on horizontal lines. The last column of the table contains the rate at which the galvanometer deflection was changing when the disk and its surroundings were at the same temperature.

Energy series were made "through air," "through red glass," and "through water cell," as in the pressure measurements. During the experiment the black coatings were frequently cleaned off from the disk and new ones deposited. The final result therefore does not correspond to an individual, but to an average coating.

To correct for any inequality between the two disk thermojunctions or any lack of symmetry in their positions, referred to the central plane of the disk, which might prevent the mean temperature of the two junctions from representing the mean temperature of the mass, series of observations were made on each face of the disks. The black coating was always cleaned off from the face of the disk away from the light. All of the series of energy measurements are gathered together in Tables VI and VII. In the tables, under the head of "through air," the first column contains the observed rate of increase in the galvanometer deflection G_1, when the disk and its surroundings were at the same temperature; the second column, the corresponding mean lamp deflections of galvanometer G_2. The third and fourth columns contain the sensitiveness of galvanometers G_1 and G_2 respectively, and the last column the values of the

TABLE V.

AUGUST 16. ENERGY MEASUREMENTS. THROUGH AIR. SERIES 4.

Zero of galvanometer G_1 (closed circuit) determined by method of cooling = 216.8 = reading at room temperature.

Time	G_1	Time	G_1	ΔG_1	Δt	$\frac{\Delta G_1}{\Delta t}$ (in mm per sec.)
0 secs.	174.5	60 secs.	253.2	78.7	60 secs.	1.312
5 "	182.0	55 "	247.3	65.3	50 "	1.306
10 "	189.0	50 "	241.3	52.3	40 "	1.308
15 "	196.2	45 "	235.2	39.0	30 "	1.300
20 "	203.0	40 "	229.1	26.1	20 "	1.305
25 "	209.7	35 "	222.8	13.1	10 "	1.310
30 "	216.4			Average............		1.307

The lamp reading (G_2) was 924.

The sensitiveness of G_2 was 667, and of G_1 was 996.

$\frac{\Delta G_1}{\Delta t}$ reduced to standard conditions becomes

$1.307 \times 667 \times 996 + (924 \times 1000) = 0.943$ mm per sec.

first column reduced to standard lamp and standard sensitiveness of both instruments. The series on the two faces of the disk are recorded and averaged separately, then combined with their probable errors in the general average at the end of Table VII.

Tables VI and VII give the following results. The average increase in the reading of G_1 for standard conditions is 0.966 mm per second. From the thermal calibration, a deflection of 9 96 divisions corresponds to a temperature difference of 1° C. Consequently the rise in temperature of the silver disk per second when the light passed:

(*a*) through air $= 0.966 \div 9.96 = (0^{\circ}.0970 \pm 0^{\circ}.00034)$ C.;
(*b*) through red glass $= 0.942 \div 9.96 = (0^{\circ}.0946 \pm 0^{\circ}.00036)$ C.;
(*c*) through water cell $= 0.880 \div 9.96 = (0^{\circ}.0884 \pm 0^{\circ}.00064)$ C.

The mass of the silver disk was 4.80 grams, its specific heat[1] at 18° C. = 0.0556; the mechanical equivalent of heat at 18° C.

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[1] U. BEHN, *Ann. der Phys.*, 4, 266, 1900.

TABLE VI.

FRONT FACE.

Date	Through Air					Through Red Glass			Through Water Cell		
	$\frac{\delta G_1}{\delta t}$	G_2 (Lamp)	S_1	S_2	$\frac{\delta G_1}{\delta t}$ Reduced to Stan.	$\frac{\delta G_1}{\delta t}$	G_2	$\frac{\delta G_1}{\delta t}$ Reduced to Stan.	$\frac{\delta G_1}{\delta t}$	G_2	$\frac{\delta G_1}{\delta t}$ Reduced
August 10..	1.387	980	990	689	0.965				0.437	345	0.864
10..	1.263	920	990	689	0.936				0.400	311	0.877
10..									0.369	279	0.902
11..	1.244	866	986	701	0.992	0.750	546	0.950	0.412	315	0.905
11..	1.455	1010	986	701	0.995	0.750	546	0.950	0.510	382	0.922
11..	1.505	1047	986	701	0.994				0.516	381	0.935
16..	1.447	1022	996	669	0.942	0.736	529	0.927	0.416	327	0.873
16..	1.284	886	996	669	0.966	0.740	527	0.936	0.451	352	0.853
16..	1.316	925	996	669	0.948	0.797	550	0.965	0.502	382	0.875
16..	1.307	924	996	669	0.943						
18..	1.598	1110	995	667	0.955	0.738	515	0.952	0.449	333	0.895
18..	1.550	1047	995	667	0.984	0.732	518	0.940	0.445	342	0.865
18..	1.548	1031	995	667	0.995	0.730	518	0.938	0.451	346	0.867
18..	1.410	957	995	667	0.977						
18..	1.330	898	995	667	0.983						
19..	1.241	862	1001	675	0.975	0.760	532	0.965	0.451	343	0.892
19..	1.360	934	1001	675	0.985	0.728	512	0.960	0.452	338	0.904
19..	1.374	905	1001	675	0.990	0.738	525	0.950	0.466	351	0.898
19..	1.364	934	1001	675	0.988						
					Average...... 0.973 ±0.003			Average...... 0.948 ±0.002			Average...... 0.888 ±0.004

TABLE VII.

REAR FACE.

Date	Through Air					Through Red Glass			Through Water Cell		
	$\frac{\delta G_1}{\delta t}$	G_2 (Lamp)	S_1	S_2	$\frac{\delta G_1}{\delta t}$ Reduced to Stan.	$\frac{\delta G_1}{\delta t}$	G_2	$\frac{\delta G_1}{\delta t}$ Reduced	$\frac{\delta G_1}{\delta t}$	G_2	$\frac{\delta G_1}{\delta t}$ Reduced
August 12..	1.374	960	991	684	0.970	0.808	578	0.949	0.495	370	0.906
12..	1.331	932	991	684	0.968	0.740	536	0.935	0.434	320	0.919
12..	1.284	900	991	684	0.967	0.765	542	0.957	0.489	371	0.895
15..	1.428	992	996	670	0.960	0.703	506	0.926	0.490	368	0.890
15..	1.428	984	996	670	0.968	0.742	526	0.941	0.466	352	0.885
15..	1.531	1068	996	670	0.962	0.765	551	0.926	0.440	337	0.873
20..	1.477	1047	996	685	0.961	0.703	522	0.918	0.458	375	0.833
20..	1.520	1090	996	685	0.951	0.760	537	0.965	0.497	400	0.848
20..	1.576	1130	996	685	0.951	0.781	570	0.935	0.507	408	0.848
20..	1.568	1124	996	685	0.950						
21..	1.783	1224	995	668	0.970	0.846	604	0.932	0.503	393	0.852
21..	1.773	1232	995	668	0.957	0.790	575	0.915	0.481	377	0.850
21..	1.705	1190	995	668	0.953	0.803	575	0.930	0.483	373	0.862
21..	1.452	1019	995	668	0.948						
					Average.. .. 0.960 ±0.0014			Average...... 0.936 ±0.003			Average...... 0.872 ±0.005
Average of front and rear face, 0.966					±0.0034			0.942±0.0036			0.880±0.0064

$=4.272 \times 10^7$ ergs.[1] Consequently the energy of the standard radiation is

(*a*) through air, $0.0970 \times 4.80 \times 0.0556 \times 4.272 \times 10^7$
or $E_a = (1.108 \pm 0.004) \times 10^6$ ergs per second.
(*b*) through red glass, $E_g = (1.078 \pm 0.004) \times 10^6$ ergs per second.
(*c*) through water cell, $E_w = (1.008 \pm 0.007) \times 10^6$ ergs per second.

REFLECTING POWER OF THE SURFACES USED.

According to Maxwell and Bartoli, the pressure in dynes per square centimeter for normal incidence is equal to the energy in ergs in unit volume of the medium. The energy in unit volume is made up of both the direct and reflected beams. If E is the intensity of the incident beam and ρ the reflection coefficient, the pressure $p = \frac{E(1+\rho)}{V}$, where V is the velocity of light. The methods for measuring p and E have already been described. The determination of ρ for both sides of the vanes C and D was made as follows. The supports of the torsion balance were replaced by the divided circular plate A (Fig. 6), of a force table which could be rotated about a central, vertical axis. The rod about which the plate turned passed up through the plate and at its top the mirror holder *bb* was fastened. The vanes were freshly silvered and mounted on a plate-glass carrier *aa*, which was held by a clamp against the back face of *bb*. The beam was directed on the vanes by the lens L_3 (Figs. 2 and 6) exactly as it had been in the pressure observations. After reflection from the vane the beam fell on a concave mirror M which projected an image of the vane upon a simple sheet bolometer B, forming the unknown resistance of a post-office box bridge. The current was supplied from storage cells and the galvanometer was the same used in the energy determinations but fitted with low resistance coils. The bolometer was covered by the bell-jar used earlier. The mirror M, the bell-jar, and bolometer were attached to the plate of the force table. The full line diagram shows the arrangement for reflection. The dotted figure shows the position for a measurement of the direct beam. All measurements of direct reflection were made for an angle of incidence of $12^\circ.5$.

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[1] Mean of Rowland's and Griffith's values. *Phil. Trans.*, 5, 184, 496, 1893.

The method of observing will be seen from the notebook record of a single series of measurements given in Table VIII. In the table, *D* and *R* indicate direct and reflected beams, respectively. The first and second columns contain the zero points and end of swings of the galvanometer G_1, and the third column, the deflection. The remaining columns, in order, contain the lamp galvanometer deflection; the deflection of G_1 reduced to constant lamp; the means of each pair of *D* and *R* values; the means of alternate readings; and the final column, the quotients of the two preceding columns which are the reflection coefficients sought. In all, three series of measurements were made on the silver, and two series on the glass-silver faces of each vane. To get average coefficients which would represent the range of condition of the mirrors during the pressure measurements, the vanes were cleaned and new silver coatings deposited between each two series on the same vane. The reflection coefficients are collected in Table IX. For each surface studied the diffused reflection for a beam which had traversed air was determined by setting the mirror holder for normal incidence. The diffuse energy reflected at an angle of 25° falling on the full aperture of the mirror *M* was measured, and the total diffuse energy for the hemisphere computed on the basis of the cosine law. It may be shown that of the diffuse reflection, two-thirds is effective as light pressure. This increases the air-silver reflection coefficients by 0.9 per cent. and the glass-silver

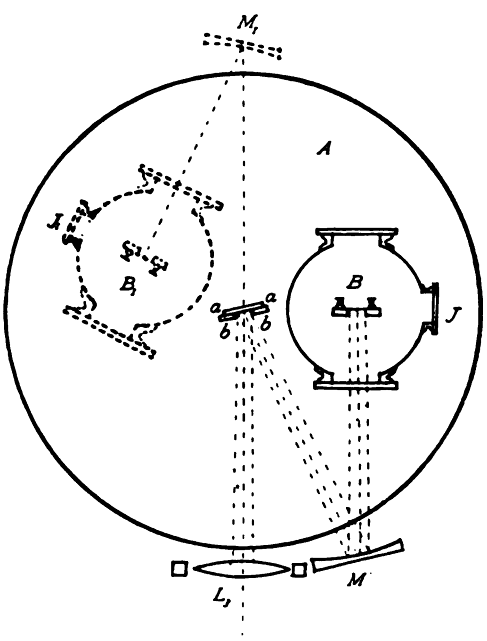

Fig. 6.

TABLE VIII.

OCTOBER 31, 1902. REFLECTION COEFFICIENT OF D_g. AIR.

G_1 Zero	G_1 Turning Point	Deflection G_1	Lamp	G_1 Reduced to Standard	Averages	Alternate Averages	Reflection Coefficient
R 350.0........	159.5	190.5	132.6	143.8	142.5		
349.0........	152.0	197.0	139.3	141.3			
D 349.5........	100.5	249.0	136.8	182.1	182.5	142.0	0.779
350.0........	111.5	238.5	130.5	183.0			
R 346.0........	177.0	169.0	119.3	141.2	141.5	182.5	.775
347.0........	171.0	176.0	124.4	141.7			
D 348.5........	123.0	225.5	124.0	181.8	182.4	141.1	.773
348.5........	120.0	228.5	125.0	183.0			
R 345.0........	172.0	173.0	122.6	141.0	140.6	182.7	.770
345.0........	171.0	174.0	124.0	140.3			
D 346.0........	132.0	214.0	115.5?		183.0	141.2	.773
346.0........	124.0	221.0	120.7	183.0			
R 344.0........	173.0	171.0	120.7	141.8	141.7	182.1	.778
344.5........	171.0	173.5	122.6	141.6			
D 346.0........	119.0	227.0	125.3	181.0	181.2	141.6	.781
346.0........	117.5	228.5	126.0	181.3			
R 342.0........	174.0	168.0	118.0	142.3	141.5	181.8	.780
342.0........	170.5	171.5	122.0	140.8			
D 347.0........	130.0	217.0	119.0	182.3	182.5	141.4	.775
347.0........	134.0	213.0	116.7	182.7			
R 341.5........	174.5	167.0	118.0	141.3	141.2		
341.0........	173.0	168.0	119.0	141.1			

Average 0.776

TABLE IX.

REFLECTION COEFFICIENTS IN PERCENTAGES.

	C_s				C_g			
	Through Air	Red Glass	Water	Diffuse	Through Air	Red Glass	Water	Diffuse
	92.8	94.5	88.9	0.98	77.8	75.9	80.8	
	89.8	90.8	86.0	0.92	77.6	76.6	80.0	1.6
	90.8			1.23				
Average..	91.1	92.7	87.5	1.04	77.7	76.3	80.4	1.6
	D_s				D_g			
	95.0	96.3	91.5	2.2	77.6	76.5	81.0	2.8
	92.0	94.0	90.4		76.7	75.2	79.7	2.2
	94.8	95.0	92.3	0.8				
Average..	93.9	95.1	91.4	1.5	77.2	75.9	80.4	2.5

TABLE IX—*Continued.*

AVERAGE REFLECTION.

	Air-Silver				Glass-Silver			
	92.5	93.9	89.5	1.3	77.5	76.1	80.4	2.0

CORRECTED REFLECTION COEFFICIENTS.

	92.0	93.4	89.0		77.6	76.2	80.5	

Average Coefficients through Air, *84.8;* Red Glass, *84.8;* Water, *84.8.*

values by 1.3 per cent. The small glass rod *d* (Fig. 1), not present in the reflection measurements, decreased the reflecting area of the silvered surfaces in the pressure measurements by 1.54 per cent. The air-silver values are thus decreased by 0.92 × 1.54 = 1.4 per cent., and the glass-silver values by 0.78 × 1.54 = 1.2 per cent. The application of these two corrections gives the final corrected coefficients in Table IX. The diffuse reflection of black coatings deposited by the method used in blackening the silver disk was measured and computed in the same manner as the diffused reflection from the vanes *C* and *D*. The agreement found by Ångström[1] between the diffuse reflection of matte surfaces for normal incidence and the cosine law was abundantly close for the present purpose. Five determinations of this reflection were made under different conditions and with different coatings. The values in percentages of the incident beam were 4.4 per cent., 4.5 per cent., 4.2 per cent., 4.6 per cent., and 5.2 per cent.; average, 4.6 per cent. Thus only 95.4 per cent. of the incident beam was absorbed by the black coating on the silver disk in producing the temperature increase observed. Hence the true energy of the beam is equal to the observed energy divided by 0.954.

The silver disk, diameter 13.3 mm, used in the energy measurements, received long waves and scattered radiation which passed round and through the light pressure vanes of diameter 12.8 mm. This amount was experimentally determined for both thin and thick silver coatings in order to approximate to the

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[1] K. Ångström, *Wied. Ann.*, **26**, 271, 1885.

average condition of the coatings in the light pressure measurements, and it was found to average (*a*) through air, 1.40 per cent.; (*b*) through red glass, 1.44 per cent.; (*c*) through water, 0.46 per cent. On this account the energy E of the standard radiation must be reduced by the above percentages.[1] Applying these corrections and the corrections due to the diffused radiation from the black coating on the silver disk, the energy of the standard radiation becomes

(*a*) through air, $E_a \times \frac{0.986}{0.954}$;

(*b*) through red glass, $E_g \times \frac{0.986}{0.954}$;

(*c*) through water, $E_w \times \frac{0.995}{0.954}$;

Hence the pressure produced by standard radiation, calculated by Maxwell's formula, $p = \frac{E(1+\rho)}{3 \times 10^{10}}$, since $\rho = 0.848$, becomes

(*a*) through air
$$= E_a \times \frac{1.848}{3 \times 10^{10}} \times \frac{0.986}{0.954}$$
$$= 1.108 \times \frac{1.848}{3 \times 10^{10}} \times \frac{0.986}{0.954} \times 10^6 \text{ dynes}$$
$$= (7.05 \pm 0.03) \times 10^{-5} \text{ dynes};$$

(*b*) through red glass
$$= E_g \times \frac{1.848}{3 \times 10^{10}} \times \frac{0.986}{0.954}$$
$$= 1.078 \times \frac{1.848}{3 \times 10^{10}} \times \frac{0.986}{0.954} \times 10^6 \text{ dynes}$$
$$= (6.86 \pm 0.03) \times 10^{-5} \text{ dynes};$$

(*c*) through water
$$= E_w \times \frac{1.848}{3 \times 10^{10}} \times \frac{0.995}{0.954}$$
$$= 1.008 \times \frac{1.848}{3 \times 10^{10}} \times \frac{0.995}{0.954} \times 10^6 \text{ dynes}$$
$$= (6.48 \pm 0.04) \times 10^{-5} \text{ dynes}.$$

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[1] As the average pitch of the cone of the incident beam was about one part in forty, no correction need be applied for inclination. Furthermore, the inside of the bell-jar was blackened and the zero of the balance was so chosen that energy reflected from the window admitting the beam could produce no pressure effects.

A comparison of observed and computed pressures follows:

	Observed Values in 10^{-5} Dynes	Computed Values in 10^{-5} Dynes	Obs.-Comp. in Percentages
Through air.........	$p=7.01\pm 0.02$[1]	7.05 ± 0.03	-0.6
Through red glass ...	$p=6.94\pm 0.02$	6.86 ± 0.03	$+1.1$
Through water	$p=6.52\pm 0.03$	6.48 ± 0.04	-0.6

An estimate of the approximate magnitude of the gas action, not eliminated by the ballistic method of observation, may be reached from the following considerations.

When radiation falls upon a vane of the torsion balance, part of it is absorbed by the silver surface. From the amounts directly and diffusely reflected, as given in Table IX, the amount transmitted by the average surface (experimentally determined but not given in Table IX), the effect of the glass rod and the reflection coefficient of the glass surface, it was found that, when the silver side of the vane was toward the radiation source, the absorption coefficient for radiation through air was 6 per cent., and when the glass surface was forward, it was 18 per cent.

The total force acting on the vane is made up of two parts, that due to radiation pressure and that due to gas action. Let F_r be the force due to the first cause,,assuming that all the radiation is absorbed, and F_g the effect due to the second, on the same condition. Then the total effect, when the silver side of the vane is forward and the radiation is "through air," is $1.92\,F_r+0.06\,F_g$. When the glass side is forward the total effect is $1.776\,F_r-0.18\,F_g$. Making these expressions equal to the reduced deflections (Table II, columns 11 and 12) on the silver and glass surfaces respectively, we have two equations by means

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[1] The pressure and energy measurements for the three different wave groups through air, red glass, and water cell, constitute three independent experiments. In the values for pressure, 7.01, 6.94, and 6.52 in the three cases are only accidentally related. The difference arises from the different reflecting power of the 45° glass plate (Fig. 2) for the different beams and from the fact that the indications of the lamp galvanometer G_2 connected with bolometer R, were probably not strictly proportional to energy for throws differing as widely as 33, 60, and 100, which, roughly, were the relative intensities of the beams through water cell, red glass, and air. The function of the lamp bolometer and galvanometer was purely to keep a check on the small variations of the lamp, which rarely fluctuated more than 10 per cent. on either side of the mean value.

of which the values of F_r and F_g may be obtained. Hence the effect due to gas action on each face of the vane is approximately determinate, as is also the part ($0.06\,F_g$) not eliminated when we average the two columns to obtain column 13.

Applying this method to all the results of Table II (with the exception of those results taken with poor mirrors as shown by our notes), the gas action present in the ballistic deflections "through air" is 0.8 per cent. Applying the corresponding data and equations to Table III, the gas action present in the red glass values is 1.1 per cent. and in the water cell values, 0.3 per cent. The sign of F_g comes out negative, which means that the gas action was suction.

This reasoning assumes that the glass faces of the vanes during the six seconds exposure are not warmed by absorption nor by the conduction of heat through the thin glass from the silver coating. The effect of any such absorption or conduction would be to diminish the computed gas action. As estimated from the static observations, the gas action in the ballistic measurements is comparable in magnitude with the computed values obtained above, and of the same sign. Both results show that the uneliminated gas action by the most liberal estimate cannot have exceeded 1 per cent. of the radiation pressure. Because of its smallness and indefiniteness no correction for gas action has been made to the final pressure values. If corrections were applied, its effect would be to reduce slightly the observed pressures.

Aside from the measurements of pressure and energy for which the probable errors are given, the percentage accuracies in the other measurements entering into the computations, and their effects upon the final result follow:

1. Quantities which affect individual series:

(*a*) Pressure values —

Period of balance T, accurate to 0.2 %; effect on result 0.0 %
Lever arm of balance L, " 0.1 %; " " 0.0 %
Constant of galv'meter G_2, " 0.5 %; " " 0.0 %
Estimate of possible error due to changing ratio of period of G_2 to length of exposure of bolometer " 0.4 %; " " 0.1 %

(*b*) Energy values—		
Constant of galv'meter G_1,	accurate to 0.1 %;	effect on result 0.0 %
" " G_2,	" 0.5 %;	" " 0.0 %
2. Quantities which affect final averages:		
(*a*) Pressure values—		
Torsion of fiber,	accurate to 0.2 %:	effect on result 0.2 %
Reducing factor, 1.357	" 0.1 %;	" " 0.1 %
Reducing factor, 1.550 for G_2	" 0.2 %;	" " 0.2 %
Reflection of surfaces of vanes	" 0.4 %;	" " 0.2 %
(*b*) Energy values—		
Mass of silver disk	" 0.1 %;	" " 0.1 %
Thermal calibration of disk	" 0.5 %;	" " 0.5 %
Diffuse reflection black coating	" 5.0 %;	" " 0.1 %

From the agreement within the probable error of the air, red glass, and water values with the theory, it appears that the radiation pressure depends only upon the intensity of the radiation and is independent of the wave-length.

The Maxwell-Bartoli theory is thus quantitatively confirmed within the probable errors of observation.

WILDER LABORATORY, DARTMOUTH COLLEGE,
Hanover, N. H., February 1903.

THE APPLICATION OF RADIATION PRESSURE TO COMETARY THEORY.

By E. F. Nichols and G. F. Hull.

In the experiments described in the foregoing paper the close agreement of theory with experiment warrants the rigid application of the radiation pressure theory in the explanation of cosmical phenomena.

In any balancing of radiation pressure against gravitation in comets the size of particles is the determining factor. The repulsion due to radiation pressure depends upon the intensity of the rays, the absorbing and reflecting power of the surface, and the cross-section of the body exposed. Gravitational attraction depends only upon mass, or the product of volume and density. It will be seen, therefore, that for spheres of a given substance the weight at a fixed distance from the Sun will vary with the cube of the radius, while radiation pressure will depend upon the radius squared. The ratio of pressure to weight will thus be inversely as the radius. This relation holds down to the point where the particles become so small that they begin to lose in absorbing and reflecting power through diffraction.

The intensity of the solar radiation and gravitation diminish with distance in accordance with the same law, so that the ratio of pressure to weight is a constant for the same body at all distances from the Sun.

For spheres of the same size, and the same absorbing and reflecting power, the ratio of pressure to gravitation is inversely as the density. The variation of this ratio, as it depends upon size and density, has been used by Lebedew[1] and Arrhenius[2] in the computation of the repulsion upon the finely divided matter of comets' tails, but the limiting value of the ratio for diminishing

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[1] *Wied. Ann.*, 45, 292, 1892; also ASTROPHYSICAL JOURNAL, 14, 155, 1902.

[2] *Lehrbuch der kosmischen Physik*, p. 150, Leipzig, 1903.

spheres of the same density due to diffraction first appears in Schwarzschild's paper.[1]

Comet heads.—In the heads of comets the phenomena are most complicated and difficult of explanation, yet it seems worth while to try to gather together a few of the separate causes which may be at work in producing this intricate structure.

The heat received from the Sun by the nucleus of a comet may be spent in three ways: (1) In raising the temperature of the nucleus. As the nucleus is of relatively small mass and probably of low heat conductivity no very considerable quantity of heat is required for this purpose. (2) Heat may be, and doubtless is, used in the vaporization of volatile hydrocarbons and other substances in the nucleus. (3) Large quantities of heat are lost from the nucleus by radiation.

The porous structure of meteorites points to a similar structure in cometary nuclei. The jets from the nucleus outward to the envelope of the head may be formed by the heating of the vaporizable materials in the interior of the nucleus and the consequent shooting out under pressure of a mixture of gases and dust through holes in a loose outer crust. Lack of sufficient means of escape in this way may cause a bursting of the nucleus sometimes observed.

The general upward current of vapors from the nucleus to the envelope, aside from jets, may be due to convection away from the more strongly heated center.[2]

Because of the counter-pressure due to the radiation of the nucleus itself, the rising of even small solid particles from the nucleus to the envelope would not encounter as strong an unbalanced pressure from the solar rays as particles in the tail. For, if all the heat received from the Sun were again radiated from the nucleus on the side toward the Sun, these two counter-radia-

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[1] *Sitzungsberichte der math.-phys. Classe der k. b. Akademie der Wissenschaften zu München*, 31, 293, 1901.

[2] Matter in the form of gases and vapors is not subject to radiation pressure, as solid and liquid particles are, because of the minuteness of molecular dimensions. Except in the spectrum regions of characteristic absorption, radiation can, theoretically, exert no pressure whatever upon a gas. Hence gases might rise from the nucleus toward the Sun practically unhindered by radiation pressure.

tion pressures would exactly balance at the surface of the nucleus.[1]

Small particles may also be aided in rising from the nucleus toward the Sun by gas forces. By numerous experiments on larger bodies immersed in a gas and illuminated on one side, it has been shown that they may be either repelled from the light source or drawn to it, depending upon the pressure of the surrounding gas (see curves, in the foregoing paper, p. 329.) If the gas pressure is not too low, particles after leaving the nucleus might first be drawn toward the Sun until a region of higher vacuum was reached in the ascent, and then be repelled.[2]

The brilliant envelope of the head may be regarded as forming at the height where condensation, caused by expansion and cooling, takes place. Here the repelling action of the solar radiation would reach a high value and the particles in the envelope would be driven backward to form the tail.

According to Arrhenius[3] this condensation in the envelope is assisted by the influx of negatively charged nuclei from the Sun, which serve as condensation centers for the ascending vapors. The height above the nucleus of the comet at which this condensation would occur would thus, in some measure, be governed by the supply of negative particles. These would be found in increasing numbers with diminishing distance from the Sun. This action may be responsible for the contraction of the head and envelope as comets approach the Sun.

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[1] It is worth noting in this connection that the longer and invisible waves are as effective in producing pressure as the visible radiations, and that these long waves strongly preponderate in the spectra of solid bodies at temperatures low in comparison with the solar temperature.

[2] It is possible also that electrostatic forces may play a small part in the formation of the head from the nucleus. Arrhenius believes the Sun to have a positive electrical charge, due to the fact that it loses more negative electrons by condensation into nuclei and subsequent repulsion by radiation pressure than it does of *positive* electrons which do not as readily serve as centers of condensation. Streams of negatively charged particles would communicate a negative charge to the matter surrounding the comet's nucleus, which would thus be attracted by the Sun. As this attraction would oppose the formation of the tail in the same measure as it assisted that of the head, it cannot be a dominating influence.

[3] *L. c.*, p. 208.

The brilliancy of the envelope may be attributed, in large part, to the fact that bodies of sufficient size to reflect solar rays are first formed out of the vapors of the head in this region. The negative nuclei from the Sun would here experience an obstruction and lose the greater part of their motion by friction. Electrical interchanges and discharges would be more active, and the hydrocarbon spectrum be brighter in the envelope than in other parts of the head.

If the brightness of the head and its envelope depend upon the number of negatively charged nuclei which strike the comet, and if, as Arrhenius maintains, the nuclei move out from the Sun radially and in greatest numbers from regions of greater solar activity, comets crossing the surface defined by solar radii drawn through the Sun-spot belts should show a marked increase in brightness, especially in maximum Sun-spot years. The writers are not aware that any such influence has been looked for in the cases where sudden changes of brightness in comets have been observed.

Comet tails.—The maximum ratio of radiation pressure to gravitation, obtained theoretically by Schwarzschild for sunlight upon opaque reflected spheres of 0.8 density, under the most favorable conditions, was about 20 to 1, if the recent estimates (ranging from 3.5 to 4) of the solar constant were used.

In Bredichin's three types of cometary tails, the highest ratio of attraction to repulsion required is about 18 to 1.[1] The multiple tails observed in such comets as Donati's may thus be satisfactorily explained by the sifting action of radiation pressure in two ways; either by assuming, with Bredichin, that the particles in the different tails are of different densities, but of uniform size, or by assuming uniform density and particles of several different sizes.

While radiation pressure alone thus affords a satisfactory explanation of comets' tails, there is no reason to assume that it is the only cause of the repulsive action observed. There are several ways in which the gases and vapors present in the tail

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[1] In comet 1893 II Hussey observed a considerably larger ratio of repulsion to gravitation.

may exert a force upon the small solid or liquid particles which are known to exist there:

1. Small particles, if warmed on one side when surrounded by gases or vapors, even under pressures so low that electrical discharges take place only under relatively high voltages, experience a strong repulsion, similar to that upon a vane of a Crookes radiometer.

2. Occluded gases or volatile materials upon the surface of the particles would be driven off by the Sun's heat on the illuminated sides, and the particles would thus receive a thrust in the direction away from the Sun.

3. If the particles were porous or loosely put together, containing cavities filled with more easily vaporizable substances, the resulting vapors would be shot out upon the hotter sides and the particles driven back by a kind of rocket action.

That these combined gas forces are still large, even in high vacua, will be seen from an actual experiment described later.

If we accept Arrhenius' theory that the solar activity produces numberless negative electrons which serve as condensation points for the vapors surrounding them in the solar atmosphere, and thus form small, negatively charged nuclei, which are driven from the Sun by radiation pressure,[1] these nuclei would exert a battering action upon the particles of the tail. In the last case a strange meeting point is found between the oldest, or Keplerian, and the latest explanation of the solar repulsion of comets' tails.

Finally Professor J. J. Thomson,[2] in investigating the action of electric waves upon charged bodies immersed in the medium, has found that a small repulsive effect may arise from this cause. This repulsive force is entirely distinct from the radiation pressure so far considered, but on the electromagnetic theory of light it may be competent to drive away electrons formed above the photosphere of the Sun, independently of the

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[1] The supposed electrical discharges in the tail of a comet which give rise to its gaseous emission spectrum are attributed by Arrhenius to the electrical disturbances caused by the influx of these negative nuclei.

[2] *Phil. Mag.*, 4, 253, 1902.

sign of the charge and of whether they have formed nuclei by condensation or not.

These last two causes of repulsion are in all probability of very minor importance when compared with radiation pressure, or even with gas action.

Experiment with a laboratory comet's tail.—Some of the above considerations led the writers to try to reproduce, as nearly as possible, in a vacuum tube some of the conditions believed to exist in comets' tails. The result of a hasty computation of the magnitude of the effect which might be expected from radiation pressure provided a suitable dust could be found was most encouraging.

At the outset it was apparent that it would be very difficult to manufacture a powder the grains of which would be sufficiently small, light, and uniform for the purpose; so the spores of a great variety of degraded vegetable forms were examined. Finally a puff ball of the genus *Lycoperdon* was discovered, the spores of which averaged two microns in diameter, and were as nearly spherical and uniform in size as a pile of apples from the same tree. These spores were light, cellular structures filled mainly with oil. They were calcined by heating to redness and all the vaporizable material driven off, leaving only sponge-like charcoal spheres behind. The density of a mass of these spheres (individuals could obviously not be dealt with) was measured and found to be about one-tenth that of water. Making liberal allowances for the spaces between spheres in the pile, the density of a single sphere could not exceed 0.15.[1]

These spores, together with a quantity of emery sand, were placed in a glass tube the form of which was suggested by the hour-glass. Smaller tubes led off from either end. One of these was fused to a good mercury pump of the Geissler type, the other bent down and joined to a small flask containing mercury.

All of the tubes were wrapped with wire gauze and heated to a temperature just below the softening point of glass and the

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[1] According to Schwarzschild's formula, the ratio of radiation pressure to solar gravitation for spheres of the size and density of these spores would be about 6 to 1.

pump was worked many hours. When the pump showed no further signs of gas, the mercury in the flask was boiled and mercury vapor driven through the tubes to carry off any permanent gases which the pump alone could not reach. After this had continued for an hour or more the tube system was sealed off from the pump and the mercury flask was surrounded by solid carbon dioxide and ether, and the hour-glass still heated. In this way all of the mercury vapor which could be condensed at a temperature of −80° C. was drawn out of the tubes. After nearly an hour the mercury flask with its frozen contents was sealed off from the hour-glass.

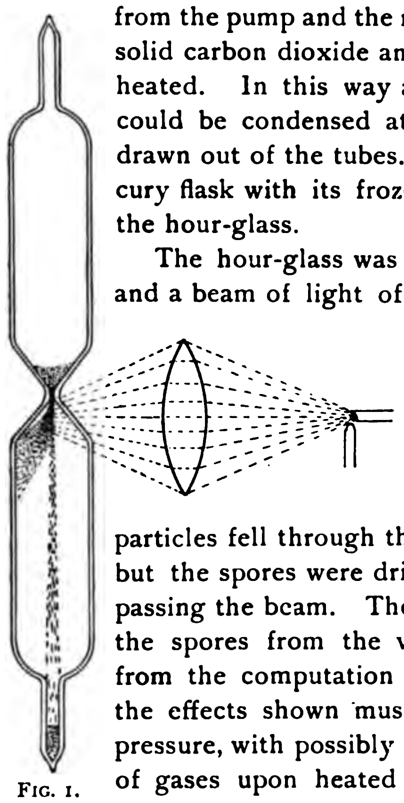
Fig. 1.

The hour-glass was then held in a vertical position and a beam of light of approximately known intensity was directed horizontally on the lower half of the tube just below the neck, Fig. 1. By tapping the tube a fine stream of sand and charcoal puff-ball spores descended. The sand particles fell through the beam, showing no deflection, but the spores were driven from the stream sidewise in passing the beam. The observed angle of deflection of the spores from the vertical was roughly that given from the computation and the observers believed that the effects shown must be due almost entirely to light pressure, with possibly a slight gas action. The action of gases upon heated bodies of this size had, so far as we know, never been studied, but one of the writers[1] had studied the gas action on larger bodies down to a pressure of permanent gases of 0.0005 mm of mercury, as shown by a McCleod gauge, and had observed that for this pressure the gas action had begun to fall off sharply. The pressure of the permanent gases in the hour-glass must have been well below

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[1] A result gained in a series of unpublished experiments on gas forces by W. v. Uljanin and E. F. Nichols. See also W. Crookes, *Phil. Trans.*, p. 300, 1878.

this value and it was thought that nearly all pressure due to vapor had been frozen out.

Later, a review of the preliminary computation was made and an error discovered which had the effect of bringing out the computed light pressure on bodies of this size and density far too large. It was plain, therefore, that the force of deflection due to gas action, probably of the character of rocket action, was at least ten times as large as the effect attributable to radiation pressure. Radiation pressure alone would produce a measurable effect under the conditions of observation, but would have been far less pronounced than the effect obtained.

The experiment had unfortunately to be tried under circumstances much more unfavorable for a pronounced effect of radiation pressure than exist in comets; for the deflection produced by repulsion must be measured in terms of terrestrial gravitation, which is over 1600 times as great as solar gravitation at the distance of the Earth. To approach cometary conditions therefore it would have been necessary to use a light beam 1600 times as intense as sunlight at the Earth. In the experiment, beams from twenty to forty times as intense as sunlight were used.

Because of the meagerness of present knowledge concerning the actual conditions in comets' tails, it is impossible to say how closely the foregoing experiment fulfilled the purpose for which it was tried. It would be difficult to prove from present astronomical data that the hydrocarbon vapors known to exist in comets' tails exert no radiometric repulsion upon the small reflecting particles present. Still more difficult would it be to show that nothing which corresponds to what has been called rocket action occurs. This latter repulsion does not require the presence of any generally diffused atmosphere whatever, but simply that the particles send off gases toward the Sun under the action of the Sun's heat. Thus in passing from the era where no adequate physical causes which would meet the required conditions could be assigned for the repulsion seen in comets, we are now likely to be embarrassed in discriminating between several contributing influences.

The writers hope to repeat the comet's tail experiment using smaller spores, if they can be found, and a tube of the new silica glass which will stand stronger heating during the pumping, and thus make it possible to reach higher vacua.

THE WILDER PHYSICAL LABORATORY,
Dartmouth College, Hanover, N. H., April 1903.

PHOTOGRAPHIC REVERSALS IN SPECTRUM PHOTOGRAPHS.

By R. W. Wood.

The importance of distinguishing between photographic and true reversals of lines in spectrograms has made it seem worth while to investigate with some care the conditions under which reversals due entirely to photographic action can occur. Professor Trowbridge has advanced the theory of selective reversibility of the silver salts in the sensitive film for certain wave-lengths, and it was in part to determine whether the tendency of a line to reverse was a function of the wave-length that the present investigation was undertaken.

As I showed several years ago, the Clayden effect, or the type of reversal giving rise to the phenomenon of dark lightning, results from the action of a light-shock on the plate before its exposure to diffuse light. The effect of this light-shock, which must be of very brief duration, is to decrease the sensibility of the plate, resulting in a less energetic action during the subsequent illumination. I made no attempt at the time to determine the maximum duration of the light-shock which would still give the Clayden reversal, but expressed the opinion that it could not exceed 1-10000 of a second. This opinion was based on a single experiment, and I have since found that by a suitable adjustment of the conditions the duration may be as great as 1-1000 of a second, though only a very slight trace of reversal occurs under these conditions.

It appears to me now that there are at least four different types of photographic reversal, or perhaps five, if we allow the chemical treatment of the plate between two exposures. As any one of these four types is liable to occur in any photographic work, when the proper conditions are fulfilled, it may be well to enumerate them at the beginning.

First type.—The ordinary overexposure reversal, which occurs when the plate is given three or four hundred times its normal exposure and then developed in the usual way.

Second type.—The reversals produced by developing the plate in full lamplight, the plate having been more or less overexposed to begin with. This type has been extensively studied by Nipher, the results of his experiments being given in the *Proceedings of the St. Louis Academy of Science.*

Third type.—This type must occur frequently, though I never remember to have seen it described. It happens when a normally or underexposed plate is developed and then exposed to light for a minute or two before the hypo bath. The fogging, which is usually of a reddish-brown color, does not occur on the portions of the plate where there is a developed image, and even if this image is very feeble it remains clean and almost transparent. I first noticed this effect in some photographs of spectra which showed strong reversals along the edges where the illumination must have been very feeble, and was unable to explain it. Further experimenting showed that it had resulted from turning up the light before the plate had been thoroughly fixed. Doubtless this effect has been described time and again in the photographic journals, but it was new to me, and may be to some others. Reversals of this type appear in the second figure of Plate XII illustrating my paper on "Screens Transparent Only to Ultra-Violet Light" (ASTROPHYSICAL JOURNAL, **17**, 136, March 1903).

Fourth type.—The Clayden effect, which is the type chiefly to be dealt with in the present paper. This occurs when an exposure of about 1-1000 of a second or less is given, and the plate subsequently fogged by exposure to diffuse light before development. If images of electric sparks are thrown on a plate and the plate then exposed to the light of a candle for a few seconds, the spark images will develop reversed, which is not the case if the exposure to candle light precedes the impression of the spark images.

Fifth type.—I have found that the condition produced in the sensitive film by light-shock can be imitated by treating the plate, after exposing portions of it to the action of a feeble light for a few seconds, with an oxidizing bath of bichromate of potash and nitric acid. If the plate is dried, and then fogged by candle light and developed, the previously exposed portions will come out reversed.

This effect is shown in Plate XXII, Fig. 4. A series of spark images was impressed on the plate, which was then covered with a piece of black paper in which a narrow slit had been cut. A number of images of this slit were then impressed on the plate by exposure to the light of a candle. If the plate in this condition were then fogged by candle light and developed, the spark images would come out reversed and the slit images not reversed. Before fogging it, one end (the upper in the print) was immersed for a few minutes in a very dilute solution of bichromate of potash, slightly acidified with nitric acid. It was then dried, exposed to candle light, and developed. In the lower portion of the print we find the sparks black and the slit images white; in the upper portion both sets of images come out dark, the reversal of the sparks being much stronger than on the untreated portion of the plate.

In the present paper I propose to discuss the Clayden effect, not only in connection with the selective reversibility hypothesis adopted by Professor Trowbridge to explain his spectrum photographs, but also in relation to the time factor, and radiations other than light, such as the Becquerel and Roentgen rays, which are quite different in their action from light.

I shall, in dealing with the subject, speak of the initial exposure of brief duration as the light-shock. The subsequent illumination which causes the reversal of the impression of the shock I shall call the fogging exposure.

The first subject investigated was the relation of the phenomenon to the wave-length of the light. The light-shock in this case was administered by exposing the plate to the spectrum of one or more sparks between cadmium electrodes by means of a small quartz spectrograph. Even with a small diaphragm the illumination by a single spark yielded a developable image of the spectrum down to the extreme ultra-violet. Six spectra were impressed on the same plate with different sized diaphragms: the plate was then exposed to the light of a candle for a few seconds and developed, the result being reproduced in Plate XXII, Fig. 1. It will be seen that the lines and the continuous background come out positive in the two upper spectra, showing that if the shock is too intense, no reversal takes place —a circumstance in which the Clayden effect differs essentially from ordinary reversal due to overexposure. Professor Trowbridge says that his reversals occur where bright lines fall on a continuous background, and considers the reversing action proportional to the product of the two effects. If his reversals are of this nature (Clayden effect), this cannot be the case, for by making one factor (the light-shock) large, no trace of reversal appears. As I shall show presently, this statement requires some modification, for as we increase the intensity of the shock, we can by increasing the fogging exposure still get reversal. As I said in my previous note, it appears to me probable that in the case of photographs of spectra of single sparks in narrow capillaries the shock was the almost instantaneous exposure to a bright-line spectrum of exceeding brief duration, followed by an exposure to a superimposed continuous spectrum of longer duration, which may have been due to incandescence of the inner wall of the capillary tube, or to phosphorescence of the gas. By employing a tube with a bore of about 0.25 mm I have obtained reversed lines in the blue with single discharges of a medium-sized induction coil and condenser.

The fact that the faint continuous spectrum of the spark is uniformly reversed shows that there is no selective reversibility so far as the initial light-shock is concerned.

I next endeavored to determine whether the wave-length of the fogging light had anything to do with the matter, in which case we should expect reversals in some parts of the spectrum and not in others, in the particular case where the fogging illumination was spread out into a spectrum, as in Professor Trowbridge's photographs.

Having already found that fogging the plate with X rays never gave reversals of spark images, it occurred to me that possibly ultra-violet light might act in a similar manner. Having impressed a number of spark images on the plate, it was illumi-

PLATE XXII.

Photographic Reversals.

nated with light of wave-length in the neighborhood of $\lambda = 2300$, from a discharge between cadmium electrodes, a screen provided with a slit being placed in the focal plane of the quartz spectrograph, with the plate a short distance behind it. The spark images were not reversed, and it appeared at first sight as if ultra-violet light of this wave-length acted like the X rays. I was, however, not willing to accept this conclusion without further study, since the fogging illumination in this case consists in reality of a number of feeble light-shocks; that is, it is of much briefer duration than in the case of candle light. In the first experiment the fogging illumination by ultra-violet light was produced by the passage of perhaps a score of sparks before the slit of the spectrograph. To get a feebler illumination of longer duration I moved the next plate to a distance of about two meters from the screen and let the coil run for about a minute. The room was absolutely dark, the spark terminals and the front of the spectrograph being covered with heavy black cloth, so that the only light that reached the plate was of the wave-length above mentioned. On this plate the spark images which had been previously impressed were strongly reversed, showing that the time factor comes into play in the case of the fogging light as well as in that of the light-shock, and that ultra-violet light is as efficient as any other, if it is not of too brief duration. This appears to dispose of the idea of selective reversibility, at least so far as the Clayden effect is concerned.

Investigation of the time factor.—To determine the maximum duration of time which the light-shock may have and still reverse, the following method was used. A disk of cardboard 50 cm in diameter was mounted on the shaft of an electric motor, the speed of which could be determined by the tracing of a tuning-fork on a smoked metal plate mounted on the same shaft. Near the rim of the disk a number of narrow slits were cut, varying in width from 1 mm to 5 mm. An arc light was focused on the rim by means of a large condensing lens, the image of the crater being about half a millimeter in diameter. By driving the disk at a high rate of speed intermittent flashes of very brief duration were obtained as the slits passed across the arc's image. A short distance behind the disk a rectangular metal tube, provided with a slit 1.5 mm wide, was mounted immediately opposite the point where the image of the arc fell on the disk. Down this tube the plate was dropped, receiving in its passage before the slit light flashes of varying duration. The plate was subsequently exposed to candle light and developed. The images of the slit in the case of the briefest flashes were perfectly sharp; in other cases they were broadened, owing to the rapid motion of the plate. This made the interpretation of some of the records difficult, and it was found better, when working with flashes longer than 1-2000 of a second in duration, to lower the plate down the tube with a thread. A print from one of these plates is shown in Fig. 2. In this case there were two 1 mm slits on the rim of the disk not very far apart, then further around a somewhat wider slit, and after this a still wider one. It will be seen that the slit images formed by the two very short flashes are completely reversed, while the others are reversed on their edges only.

If the plate moves during the exposure, as was the case in this photograph, it is obvious that the edges of the slit image will receive less exposure than the center, which accounts for the partial reversal. As the result of exposing about two dozen plates, it was found that the duration of the shock could be as long as 1-1000 of a second, and still yield reversals. It was only by carefully regulating the intensity of the fogging light and the duration of the development that these reversals could be obtained. When the duration is less than 1-2000 sec. reversals could be obtained without difficulty. Flashes varying in duration from 1-15000 sec. to 1-500 sec. were studied, and it was found that as the duration of the shock was increased the reversals became weaker, the images finally failing to appear at all on the plate, notwithstanding the longer duration of the flash. On still further increasing the duration the images came out not reversed. There may be some connection between the condition in which the light-shocks fail to develop at all, and the zero condition of the plate described by Nipher.

The experiment in which the fogging of the plate was effected by exposure to ultra-violet light furnished by a quartz spectrograph shows that the time factor plays a rôle in the case of the fogging light as well as in the light-shock.

It was found that if the fogging light was rather intense, but of short duration, the image of the light-shock did not reverse; if the light was less intense, but of a little longer duration, no trace of the shock appeared; while if the light was still less intense, and of somewhat longer duration, the image came out reversed. With a suitable ratio of intensities and durations of time, it is possible to superpose two impressions on a photographic plate, only one of which appears on development.

This effect is shown in Fig. 3. A series of spark images of equal intensity was impressed on the plate, which was then fogged in sections, the lower strip being exposed to the light of one spark at a distance of a meter, the next to the light of four sparks at a distance of two meters, the next to nine sparks at three meters, and so on. The total amount of fogging light was thus approximately the same in each case, though it was found that considerably greater action was produced by a large number of sparks at a considerable distance than by a single spark close to the plate. It will be noticed that on the third strip from the bottom there is scarcely a trace of the spark images. The ratio of the times of duration of the shock and the fogging light was in this case about 1 : 9. On the two strips below this one the sparks appear not reversed, while on all the strips above reversal has taken place.

A more careful quantitative investigation of these effects is much to be desired, with apparatus of such design that the duration and intensity of both the light-shock and fogging light can be accurately controlled.

I am of the opinion that the result of such an investigation would be the establishment of the fact that with very brief and intense light-shocks, comparatively intense fogging light of short duration will yield reversals, while in the case of shocks of say 1-1000 second duration, the fogging light must be feeble and of long duration in order that reversals may be obtained. My plates appear to indicate this qualitatively, but quantitative data could doubtless be obtained with suitable apparatus. As I shall show later, it is possible to administer the shock in such a manner that it comes out reversed even when the fogging light is the flash of a single spark.

I have tried to obtain some idea of the action of the light-shock, by attempting to transform its effect on the plate into an effect similar to that produced by ordinary exposure, by means of the action of various chemical agents. These experiments were all failures, but the interesting fact was ascertained that an ordinary exposure appeared to be transformed into a shock exposure by the action of a dilute bath of bichromate of potash slightly acid with HNO_3. This effect is shown in Fig. 4. A series of spark images was impressed on the plate, and then a series of images obtained by illuminating the plate with the light of a candle shining through a slit in a piece of black paper. One-half of the plate was then dipped into the bath, washed and dried, exposed to the light of a candle, and developed. A print from this plate is reproduced in Fig. 4. On the upper portion, which was treated with bichromate, both the spark images and slit images appear reversed; on the lower the latter are not reversed. This experiment merely shows that a plate which has been exposed to light in certain places and then treated with the bichromate solution is less sensitive to the action of subsequent illumination on the spots which have previously received light. The condition may appear at first sight to be similar to that produced by a light-shock, but there is in reality no connection between the two, for while light-shocks not followed by fogging can be developed as not reversed images, the "bichromatized images" do not develop at all, unless the plate is fogged before development.

The nearest approach which I have been able to make to the transformation of the effect of a light-shock into that due to ordinary exposure, is by the action of the X rays. It was found that spark images could not be reversed under any circumstances, if the plate was fogged by these rays instead of candle light. To prove that the case was not analogous to the one in which ultra-violet light failed to give reversals owing to the comparatively brief duration of the illumination, long exposures were made with the X-ray tube at a considerable distance. Not only were reversals never obtained, but it was found that, after a brief exposure to the rays, fogging the plate by lamplight failed to reverse the spark images. This seemed very remarkable, for it was subsequently ascertained that X-ray images could be reversed even when produced by long exposure to feeble radiation, by subsequent exposure of the plate to lamplight. This effect is shown in Plate XXII, Fig. 5.

The spark images were impressed first. The plate was then exposed in vertical strips to the action of the X rays for varying lengths of time, the left-hand strip receiving the longest exposure, while the right-hand strip was not exposed at all. Following this, came an exposure in horizontal strips to lamplight, the lower strip having the longest exposure, and the upper none at all. It will be seen that there is no trace of reversal in the upper left-hand corner, where the fogging is due almost wholly to X rays, while reversed edges appear on all of the sparks in the lower right-hand corner, where the fogging was due to light; moreover, in the lower left-hand corner, where the X-ray fog preceded the light fog, the images are not reversed.

On investigating the matter further I found that shocks administered by single powerful flashes of X rays were reversed by subsequent exposure to lamplight. In this case, however, the time element appears to be without much influence, for images formed by long exposure to very feeble X radiation reverse in the same manner. This seems very remarkable, when we consider the fact that exposure to these rays changes the condition produced by light-shock in some manner, so that it is impossible to reverse it by further fogging.

The reversal by X rays is illustrated in Fig. 6. A plate was wrapped up in black paper and exposed to the radiation for several minutes, a vertical iron rod shielding the center strip of the plate. The plate was then exposed to lamplight for different lengths of time in strips perpendicular to the shadow of the iron rod. On development it was found that on the end of the plate which had received the shorter exposures to light, the central strip came out lighter than the background, while on the opposite end of the plate it was darker. At a certain point near the center of the plate all trace of the shadow of the rod had disappeared, showing that exposure to X rays for some time and then to light for a certain time produces an image no blacker than the light alone would have produced.

I next ascertained that if the plate be exposed simultaneously to light and X rays, the latter inhibit the action of the former. A candle and an X-ray tube were set up at some little distance apart in front of a plate, the latter being much nearer the plate, however, owing to its less energetic action. An iron rod mounted in front of the plate cast two shadows upon the sensitive film, one projected by light, the other by X rays. After exposure the plate was developed, with the curious result that one shadow was darker than the background, the other lighter, showing that the light was more energetic in its action on the area screened from the X radiation. It may be worthy of mention that both this result and the preceding one were predicted before the actual experiments were tried. The prediction was the result of an attempt to apply Bose's strain theory of photographic action[1] to the phenomena in question. This theory seemed rather promising at first, especially as it enabled me to predict new phenomena, but it failed to account for so many things that I was finally forced to abandon it.

The action of other stimuli was next investigated. It has long been known that pressure marks on the film can be developed. I found that if the plate was fogged by lamplight before developing, the pressure marks came out reversed. It then occurred to me to try the effect of light-shocks on pressure marks, and I found to my surprise that the flash of a single spark was as effective in reversing the pressure mark as the exposure to the lamp. The pressure marks can also be reversed by exposure to X rays.

As a result of numerous other experiments, I finally found that if we arrange the stimuli in the following order, pressure marks, X rays, light-shock, and lamplight, an impression of any

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[1] J. C. Bose, *Proc. Roy. Soc.*, 70, 185, 1902.

one of them can be reversed by subsequent exposure to any other following it in the list, but under no circumstances by any one preceding it. For example, pressure marks can be reversed by any one of the other three stimuli, while X-ray images are reversed only by light-shock and lamplight.

Experiments with Becquerel rays have given rather uncertain results. Pressure marks can be reversed by them, and they in turn can be reversed by lamplight, but these were the only two cases in which reversals were obtained, which makes it difficult to fit the rays into the series and still have the rule hold.

These experiments show that the effects of the different kinds of stimuli on the sensitive film are quite different. Much more experimental work will have to be done before any definite notion can be obtained as to the nature of the changes produced by the action of radiation of any sort, and it is hoped that the experiments described in this paper may prove suggestive to others. Doubtless an exhaustive study of the action of various chemical agents on the plate between the two exposures would throw much light on the cause of the reversals.

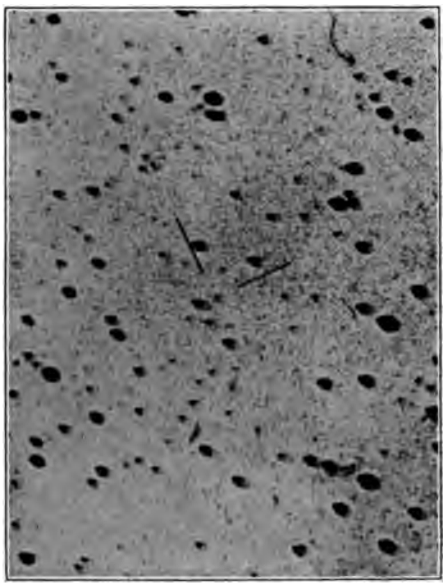
If I interpret the strain theory correctly, the application to these phenomena would be to assume that the light-shock produces a negative strain, while lamplight produces a positive strain, either of which yields an image on development. The reversal in cases where the lamplight follows the impression of the light-shock could be explained by assuming that the negative strain has to be undone before the positive strain can begin; consequently these parts of the plate lag behind the parts which have not received the light-shock. We should then have to assume that the positive strain once started can be continued by a stimulus which, acting first, would have produced a negative strain, in order to account for the fact that exposures to lamplight are not reversed by light-shocks. Moreover, it is difficult to explain on the strain theory that two different stimuli acting in succession may produce only the same effect as one of them acting alone. It appears to me that the strain theory would lead us to suppose that the negative strain produced by the first stimulus might be exactly neutralized by a stimulus which produces a positive strain, the plate returning to its original condition, *i. e.*, not darkening on development. This is never the case.

In cases where reversed lines appear in the spectrum which are suspected of being photographic in origin, *i. e.*, not true absorption lines, the following precautions should be taken. Repeat the exposure a number of times, using successively smaller diaphragms in front of the prism. If the reversal is ordinary solarization due to overexposure, it should disappear when the intensity of the light is sufficiently reduced. It seems to me that in such cases the reversed line should be bordered by bright edges, which does not seem to be the case in the photographs published by Professor Trowbridge. If the Clayden effect is suspected, the source of light should be examined with a revolving mirror, to determine whether a dual illumination is present. The speed of the mirror should not be too great, otherwise the phosphorescence (if it exists) which follows the very brief bright line flash, may be spread out to such an extent that no trace of it appears. This may account for the failure to obtain evidence of a dual illumination in the case of the heavy discharges in quartz tubes.

JOHNS HOPKINS UNIVERSITY,
Baltimore, Md.,
May 1903.

PLATE XXIII.

N.



S.

Scale 1 mm = 13″.

REGION OF *NOVA GEMINORUM*

February 21, 1903.

NOVA GEMINORUM.

AN EARLY PHOTOGRAPH AND PHOTOMETRIC MAGNITUDES.

By J. A. PARKHURST.

THE negative of the *Nova* region taken 1903, February 21, $8^h\ 22^m$ to $8^h\ 42^m$, C. S. T., was mentioned in *Bulletin* No. 19 of the Yerkes Observatory,[1] but the cut made to illustrate it was not successful and was therefore omitted. An untouched copy is reproduced here, Plate XXIII, showing a star of magnitude 14.5 apparently coincident with the present position of the *Nova*. The photometric magnitudes of four faint stars near the *Nova* are as follows:

Star No.	Mag.	Measures
5..........	13.11	3 nights
6..........	12.99	2 "
3..........	14.89	1 "
1..........	13.34	1 "

The numbers given for identification are those on Professor Barnard's drawing of the region on page 304 of the *Bulletin* No. 19. It will be seen that the *Nova* is a little brighter than star No. 3; its magnitude on February 21 is therefore estimated at 14.5. It will be noticed that the photograph agrees with Professor Barnard's micrometer measures in placing the *Nova* farther north than star No. 1, whereas the object taken for the *Nova* on the photograph by Mr. Dugan at Heidelberg February 16, and reproduced in *Popular Astronomy* for May 1903, page 260, is a little farther south than star No. 1, possibly due to the retouching of Mr. Dugan's print.

Following are the photometric magnitudes of the *Nova*, preceded by a list of standard stars and the comparison stars so far used. The standards, *l*, *g*, and *h*, were measured both at Har-

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[1] ASTROPHYSICAL JOURNAL, 17, 300, May 1903.

vard (*H. C. O. Annals*, Vol. XLV) and at Potsdam, the difference between the means, 0.20 magnitude, agreeing closely with the systematic difference between the two catalogues; these stars seem therefore well adapted for standards. For the comparison stars, *b*, *c*, *d*, and *e*, the magnitudes given in the columns headed H. and P. are the means of three nights' comparison with the standards given above, H. being on the Harvard basis, and P. the Potsdam.

STANDARDS.

Harvard and Potsdam.

Star	*B. D.*		*H. C. O.*	*P. D. M.*
	No.	Mag.		
f......	+29° 1307	7.2	7.36	7.22
g......	30 1318	7.0	7.13	7.50
h......	31 1363	7.0	7.23	7.60
	Mean		7.24	7.44

COMPARISON STARS.

Star	*B. D.*		H.	P.
	No.	Mag.		
b......	29° 1342	8.2	7.79	7.99
c......	29 1320	7.8	7.46	7.66
d......	30 1306	8.6	9.09	9.29
e......	30 1302	9.2	9.32	9.52

MEASURED MAGNITUDES OF THE *NOVA*, BASED ON THE HARVARD SCALE.

	G. M. T.	Mag.	Seeing		G. M. T.	Mag.	Seeing
1903, March	27.715	8.51	fair	1903, April	7.574	9.19	clouds, moon
	28.636	8.71			8.593	9.19	moon
	29.603	8.85			16.661	9.31	good
	30.673	8.76	fair		26.671	9.63	fine
	31.588	8.89	good		27.632	9.41	good
April	3.564	8.91	clouds		30.591	9.74	good
	4.583	8.96	moon	May	3.621	9.56	moon
	6.574	9.19	moon		6.634	9.50	
					7.593	9.84	moon, good

The resulting magnitudes of the *Nova* should be compared with Professor Barnard's (given elsewhere in this number), which are based on photometric measures of comparison stars, on the Harvard system.

Fluctuations, similar to those of *Nova Persei*, are clearly shown, as indicated in the measures given in *Bulletin* No. 19, and noted in Harvard *Circulars* Nos. 127 and 128.

YERKES OBSERVATORY,
May 9, 1903.

OBSERVATIONS OF *NOVA GEMINORUM.*

By E. E. Barnard.

My estimates of the magnitudes of the *Nova* were made by comparison of its light with neighboring stars, the magnitudes of which have been determined by Mr. Parkhurst with the photometer.

The instruments used were the finders of the forty-inch and twelve-inch refractors, and on the last few dates (May 7, 8, 9, and 10) the twelve-inch, as the star could not be seen in the finder because of moonlight and haze.

The observations of April 27 were made through a very hazy sky, and the estimations were more or less difficult.

At first the *Nova* was of a strong red color, but it has since become colorless. On March 29 there was not much color seen in the twelve-inch, though it was a little redder than *B. D.* +29° 1342. On April 3, with the same instrument, it was noted as "a little reddish;" April 22, also with the twelve-inch, it was colorless and there seemed to be a slight difference of focus. On April 27 and 28 no trace of color was seen with the forty-inch.

In the first observations the *Nova* showed no difference in focus from that of an ordinary star (see Astrophysical Journal, **17**, 302, 1903). In the later observations there seems to be a sensible change in the focus; this, however, has not been properly verified.

On April 27 careful observations for focus were made with the forty-inch, with the following results:

Focus for *Nova*, scale reading	-	2.36 in. (5 obs.).
Focus for star, scale reading	-	2.28 in. (5 obs.).
Difference, *Nova*—star	-	= + 0.08 in. (= 2.0 mm).

The seeing was poor and the settings discordant for both objects. I think, however, that this indicates a real change of focus, for when either object was in the best focus the other was somewhat ill-defined. Cloudy weather has since prevented verification of this with the forty-inch.

On April 6 the crimson image seen on March 30 (*loc. cit.*, p. 303) was still present, though not so strong and definite. On April 27 it had entirely disappeared, the out-of-focus image of the *Nova* resembling that of an ordinary star. Cloudy weather had prevented any observation by me with the large telescope between April 7 and 27. I am therefore unable to say just when this change took place; it would perhaps not be far from the middle of April.

OBSERVED MAGNITUDES OF *NOVA GEMINORUM*.

		Central Standard Time.		Mag.
1903, March	27	12^h	30^m	8.00
	29	9	0	8.81
	30	9	0	8.82
	31	7	20	8.84
April	3	8	0	8.96
	4	7	40	9.04
	6	9	0	9.15
	7	10	20	9.22
	9	8	0	9.12
	16	7	40	9.12
	17	9	0	9.20
	22	7	50	9.20
	24	8	15	9.92
	26	8	30	9.81
	27	8	30	9.96
	28	8	30	10.18
May	3	8	20	9.80
	6	8	10	9.80
	7	9	10	9.87
	8	8	30	9.77
	10	8	10	9.77
	18	8	30	10.02
	19	8	30	10.07

At the observation of March 27 the star was very low and the estimated magnitude is unreliable.

YERKES OBSERVATORY,
May 11, 1903.

MINOR CONTRIBUTIONS AND NOTES.

PARALLAX OF THE BINARY SYSTEM δ *EQUULEI*.[1]

THE object of this communication is to present a value of the parallax of δ *Equulei* obtained by using as data the elements of the orbit derived from micrometrical measures and the relative velocity of the components in the line of sight furnished by spectroscopic observations. While the result given is merely provisional, one to be improved when better elements of the orbit are available, as they no doubt will be after two or three years more, yet it is thought that it has already a measure of certainty which places it in the list with the more accurately determined stellar parallaxes. Moreover, the manner of its derivation differs from previous determinations. The use of comparison stars and the uncertainties of their assumed distances are eliminated. In theory the method leads to an absolute value of the parallax, and not to a relative one, as is necessarily the case when comparison stars are employed.

The mathematical relations connecting the elements of the orbit of a binary, the relative velocity of its components in the line of sight, and the parallax of the system, have long been known. Applications have hitherto been wanting, for the reason that no double stars had been found which furnished all the data needed. δ *Equulei* has proven an exception. The elements of its orbit are approximately known, and in 1901, at the time of the last periastron passage, the relative velocity of the components in the line of sight was so great that the spectra of the two stars were displaced to a measurable extent.

In the *Monthly Notices* of the Royal Astronomical Society for March 1890, Professor Arthur A. Rambaut has given the following simple formula for computing the parallax of a binary from the data here considered:

$$\pi = \frac{la^2 \sqrt{1 - e^2} \sin (\phi - \lambda) \sin i}{VPr \sqrt{1 - e^2 \cos^2 \phi}} .$$

In this equation P denotes the periodic time, a the mean distance, e the eccentricity, i the inclination, r the radius vector, λ the angle

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[1] *Lick Observatory Bulletin* No. 32.

between the line of nodes and the major axis of the true ellipse, ϕ the angle between the tangent to the orbit and the major axis, V the relative velocity of the components in the line of sight as furnished by the spectroscopic observations, l the velocity of the Earth in its orbit, and π the parallax of the system.

The elements of the orbit of δ *Equulei* are still imperfectly known. A nearly continuous record of the motion of the companion during the next three years is necessary to remove effectively the uncertainties which still exist in their values. Eight times since the discovery of this binary the companion has passed over the arc which it will describe during the next three years, and numerous observations relate to this portion of the orbit. But the measures are more or less discordant, and on this account additional ones are required to fix with certainty the direction and magnitude of the greatest apparent distance. When these measures are obtained and the elements of the orbit revised, we shall have the data which will give an accurate value of the parallax of the system. A consideration of the material at present available appears to show that the changes which will probably take place in the elements due to the revision of the orbit will not greatly alter the value of the parallax which may now be derived, and it is on this account that a provisional value is here presented.

During the past three years this binary has been followed closely at the Lick Observatory and much has been done to advance our knowledge of its orbit. It has been shown that the periodic time is about 5.7 years; that the last epoch of periastron passage was about 1901.5; that the apparent distance at periastron is about 0ʺ.15; that the inclination is greater than given by the trial elements which I printed in the *Publications of the Astronomical Society of the Pacific* for December 1900, and afterwards in Vol. V of the *Publications of the Lick Observatory*, being perhaps as much as 82° or 83°; and that the mean distance is probably a little larger than given by those elements. Further, it is known that the line of nodes and the projection of the major axis of the orbit are nearly coincident.

If we retain the line of nodes and the angle between the line of nodes and the major axis, the true ellipse as given by my published elements, and put the mean distance equal to 0ʺ.28 and the eccentricity equal to 0.46, we get 0ʺ.151 and 0ʺ.409 as the periastron and apastron distances.

The relative velocity of the components in the line of sight at the epoch of periastron passage, as determined by the observers using the

Mills Spectrograph,[1] was about 20.3 miles per second. At the same time the Earth's orbital velocity was about 18.2 miles per second. At periastron ϕ becomes 90° or 270°, and with $\lambda = 179°$, we have $\phi - \lambda = 91°$. Substituting these values in Professor Rambaut's formula we get

$$\pi = 0''.071.$$

It is evidently impossible to give the probable error of this result. Some of the quantities upon which it depends are much better determined than others. It happens that those which appear to be the most uncertain may vary considerably without greatly affecting the resulting value of the parallax. For example, considerable variations may take place in the values of i and λ without greatly changing the values of sin i and sin $(\phi - \lambda)$ which appear in the formula. Of the other quantities those which appear the least certain are the mean distance and the eccentricity. From a consideration of all the past measures it appears highly improbable that the apastron distance can be as much as 0''.05 greater or less than the value used above. If we vary the apastron distance and eccentricity together so as to keep the already well-determined periastron distance constant, and further retain the other elements of the computation as used above, we shall find that the apastron distance and parallax increase together, but the former at about four times the rate of the latter. From this consideration it appears improbable that the parallax will be altered so much as 0''.012 owing to changes which take place in the values of a and e due to the revision of the elements of the orbit.

The mass of the system corresponding to the parallax given above, and the mean distance and the periodic time used in its derivation, is 1.89, the mass of the Sun being taken as unity. The components of this pair are slightly unequal in brightness, and perhaps also in mass. One may be as massive as the Sun, but it cannot much exceed it.

The mean distance at which these stars perform their revolutions is about four times that of the Earth from the Sun. But owing to the eccentricity of the orbit the range in distance is enormous. At periastron the stars are separated by a space only a little greater than two astronomical units, while at apastron it is five of these units.

It would form an interesting analytical problem to investigate the effect of tidal action upon the relative orbit of this system. The data are pretty well ascertained. Broadly speaking the stars have spectra

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[1] *Bulletin of the Lick Observatory* No. 4, and *Publications of the Lick Observatory*, 5 211.

of the solar type, and being comparable with the Sun in mass, it would seem not unreasonable to assume that their densities are approximately the same as that of the Sun.

WILLIAM J. HUSSEY.

FEBRUARY 23, 1903.

TWO STARS WITH VARIABLE RADIAL VELOCITIES.

IN the course of our most recent work with the Bruce Spectrograph on stars having spectra of the *Orion* type the two stars u *Herculis* and 57 *Cygni* have been found to show large variations in their radial velocities.

The data for these stars are as follows:

u *HERCULIS* ($\alpha = 17^h\ 14^m$; $\delta = +33^\circ\ 12'$; Mag. = 4.9).

Plate	Date	Taken by	Velocity	No. of Lines	Measured by
C23	1903, February 19	A.	− 65	5	A.
C34	March 18	F.	− 44	3	A.
DB6	May 7	A.	+101	4	A.
DB17	May 9	A.	+ 98	3	A.

This star is of especial interest on account of being a photometric variable of irregular period. The lines of its spectrum are broad and diffuse, and the measures are consequently uncertain to the extent of several kilometers.

57 *CYGNI* ($\alpha = 20^h\ 50^m$; $\delta = +44^\circ\ 0'$; Mag. = 4.6).

Plate	Date	Taken by	Velocity	No. of Lines	Measured by
DB22	1903, May 16	F.	−114	4	F.
DB24	May 17	A.	− 23	3	F.

On plate 22 the magnesium line at λ4481.4 appears to have a second component, which is displaced toward the red by an amount corresponding to a velocity of about +56 km. No second component can be seen on plate 24. In this connection it may be stated that on different plates we often find marked differences in the distinctness of the lines in spectra of stars varying rapidly in velocity, doubtless in part due to the change of velocity during the exposure.

In the list of plates given above those belonging to series C were taken with the short-focus camera, to which reference has already been made in our communication in the April number of this JOURNAL.

The plates of series DB were taken with a dispersion of one prism and the regular camera of twenty-four inches focal length. For this apparatus two of the prisms of the Bruce spectrograph are removed, and auxiliary castings added to support the camera tube at the necessary angle in reference to the first prism. Especial attention was given to the stability of the support, and the results obtained are entirely satisfactory in this respect. The scale of the plates is, of course, very closely one-third that given by the three prisms. In the case, however, of stars which have wide and diffuse lines in their spectra, the narrowing of these lines, and the consequent increase in the accuracy of the measures upon them, largely counteracts the effect of the smaller scale, so that the final values often compare favorably with those obtained with the use of the higher dispersion. The considerable increase in the number of measurable lines, through the additional extent of spectrum which is brought into focus, also contributes materially to this result.

EDWIN B. FROST AND WALTER S. ADAMS.

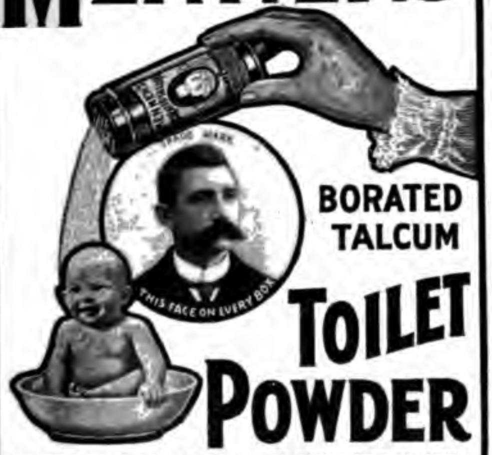
YERKES OBSERVATORY,
May 19, 1903.

INDEX TO VOLUME XVII.

SUBJECTS.

INDEX TO VOLUME XVII.

AUTHORS.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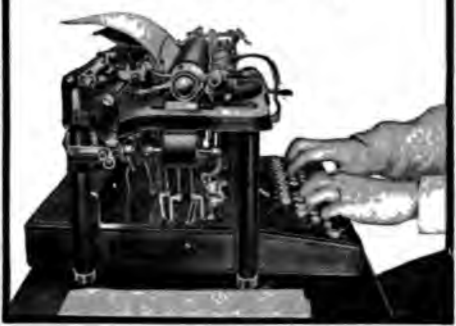


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